Application of natural and synthetic fibres as a replacement for asbestos fibres in cement boards

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Application of Natural and Synthetic Fibres as a Replacement for Asbestos Fibres in Cement Boards

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Abstract

The use of asbestos fibres in construction products has been banned in European countries for about two decades due to its effect on human health. At present, many developing countries use asbestos cement board as one of the most important construction products for roofing, cladding and partition walls. The Hatschek process is the most commonly used method to produce asbestos Fibre Cement Board (FCB).

There are two major problems for the asbestos FCB manufacturers in replacing their products with non-asbestos FCB. The first one is finding materials and fibres that are available and competitive in price compared to asbestos fibres, and the second is providing inexpensive machines and equipment to produce non-asbestos FCB.

In this research, an effort has been made to solve these two major problems. After the initial laboratory investigations on several natural and synthetic fibres some of the fibres with potential use in FCB were chosen for the further investigations. A slurry vacuum dewatering process was then designed and made for the laboratory use. The performance of material selections and mix designs selected from the laboratory studies were subsequently verified with factory Hatschek process in a factory site trial.

Many specimens with natural and synthetic fibres incorporating silica fume and limestone powder were made and tested in the laboratory. Silica fume and limestone powder were used for enhancing flexural strength and suppression of alkalinity to reduce breakdown of the cellulose fibres. The results of mechanical, physical and

durability tests were analysed. The microstructure of the fibres and composites was also studied by SEM (Scanning Electron Microscopy).

At some stages, mix design optimization was carried out to gain the highest flexural strength. The most suitable mixes were chosen for the factory site trials. A number of full-scale non-asbestos trial boards were made successfully in an asbestos FCB factory and tested in accordance with the current national and international standards. The results indicated that the trial boards fulfilled the requirements of the relevant standards.

Based on the outcome of this research, a combination of acrylic fibres and waste cardboard in a mix incorporating silica fume and limestone powder in addition to Portland cement can be used to replace asbestos fibres. Although broadly compatible with the asbestos cement production process, this formulation change will necessitate some changes to the existing production lines in asbestos cement factories to produce non-asbestos FCB.

Keywords: *Cement composite, Fibre cement board, Natural fibres, Synthetic fibres, Properties of cement board.*

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Chapter 1: Introduction

1.1 General background

Fibre Cement Board (FCB) is one of the most important construction materials that have drawn much attention during the past half-century. It can be used in flat and corrugated shapes as a material for roofing and in many other shapes for internal walls, external walls and cladding. The most important method used to produce FCB is the 'Hatschek' process, which was established in early 1900s. For more than half a century, only asbestos fibres were used to produce FCB around the world. In the early 1970s, clinical research showed the many harmful effects of asbestos fibres on human health (Murie 2008). So the use of asbestos in new construction projects was banned for health and safety reasons in many developed countries, including the European Union and Australia.

Currently there are several alternative synthetic fibres such as PVA (poly vinyl alcohol and Polyacrylonitrile) to replace asbestos. Only a few countries such as US, Belgium, Australia, Germany etc have the technology and fibres to produce non-asbestos cement composite. Other countries with a ban on the usage of asbestos such as Greece, Poland, Ireland, Cyprus etc adopted similar processes to produce FCB by importing these fibres and this technology. Since acquiring this technology is expensive, some institutes and companies (such as Shera in Thailand and Betopan in Turkey) have succeeded in finding more economically viable alternatives such as special cellulose fibres, some admixtures and additives and they keep this technology secret.

One of the recent international congresses regarding asbestos usage in the world was held in 2008 by the Building and Woodworkers' International (BWI) who have been advocating a worldwide ban on asbestos since 1989. Fiona Murie, the BWI's Director of Health and Safety announced that in many developing countries, where there is poverty, low life expectancy, non-unionized workplaces and exploitative labour practices, people are exposed to asbestos on a daily basis and have no idea of the hazards they are facing. Then she concluded that the estimation of WHO for 100,000 asbestos related deaths/ year is a serious underestimate. (Murie 2008). These countries have not been able to access the non-asbestos FCB technology, mainly because of the high costs and the monopolization of the technology by Western companies.

Iran is one of the developing countries that uses asbestos as the main fibre in FCB. Despite widespread bans on the use of asbestos in the developed world, there are ten FCB factories in Iran and they all use asbestos in their products. The annual amount of asbestos used has increased since 1990 and was about 80,000 tonnes in 2000 (Virta 2006). The available statistics show that the Iranian production of flat and corrugated cement board is in excess of 30,000,000 m^2 and production of composite cement pipes in excess of 4,000 km. Also, according to the annual report of the Ministry of Health of Iran, the number of deaths due to asbestos-related diseases is about 1,000 per year. Therefore, development of non-asbestos cement composite is important for Iran and other developing countries.

Iran's Environment Protection Organization (IEPO 1998), after accepting the hazard of asbestos fibres to health in 1998, legislated to remove asbestos fibres in construction industries within seven years if an alternative was to be found. As an alternative has not

been found so far, the factories continue to use asbestos fibres. The majority of FCB factories in the world, and all existing factories in Iran, use the Hatschek process. Therefore, it is vital that new techniques should be compatible with available equipment with minor adjustments, such as the addition of pulper or rollers in the production line.

1.2 Research background

Over the last decades many research projects related to the substitution of asbestos by different types of materials and fibres have been conducted. These attempts have focused on using natural cellulose fibres and synthetic fibres, alone or as a mixture (Coutts 2005). However, some of studies have concentrated on mineral fibres such as glass, wool and slag fibres (Purnell et al. 1999). The most important fibres that have been studied are plant fibres, such as wheat stems, sunflower stems, eucalyptus, sisal, bamboo, flax, banana, jute, bagasse and kraft fibres (Asasutjarit et al. 2007 and Coutts 2005). The results show that the latter has attracted the most attention because of its mechanical and physical characteristics, compatibility with the cement matrix, availability and relatively low costs. However, it requires a suitable treatment before use in FCB to prevent decomposition and decay in the alkaline environment of the cement (Negro 2006 and Roma Jr et al. 2008). Nowadays, most of the factories that have modified the Hatschek method use kraft fibres as the primary fibres along with other synthetic fibres. To describe this technology in more detail, some results of research achievements are discussed below.

Asasutjarit et al (2007) and Coutts (2005) have indicated various advantages in the use of natural fibres in cement composites (i.e. increased flexural strength, post-crack load bearing capacity, increased impact toughness and improved bending strength). Bilba et

al (2003), Juárez et al (2007) and Negro (2006) have shown that natural fibres exhibit many advantageous properties as reinforcement for composites in the Hatschek process. And Roma Jr et al (2008) have illustrated each particular fibre type requires special modification and treatment to improve its vulnerability to chemical decomposition in the alkaline environment of cement.

The author studied (Khorami et al. 2009) application of natural and synthetic fibres to produce fibre cement board using Iranian waste agricultural by-products. The study showed that some fibres such as bagasse have a huge potential when compared with other Iranian agricultural by-products to be used in FCB. The study also illustrated that manufacturing cement board with synthetic fibres solely cannot satisfy the requirements of relevant standards and is not recommended to be used in Hatschek process.

1.3 Aims and objectives

The aim of this research is to use fibres and materials that are readily available in most countries and could be suitably processed to be used in FCB production with economic justification. The cement board made out of those fibres should meet the requirements of the relevant standards. Meanwhile these fibres should not be harmful to human health.

The outcome of the research should be applicable to the existing FCB factories, which use the Hatschek process for their products.

In addition to the aforementioned primary aims, there are also some objectives:

- To study the effect of natural and synthetic fibres on the characteristics of FCB.
- To study of the effect of the fibre content on the characteristics of FCB.

- To study of the effect of additives such as silica fume and limestone powder on the characteristics of FCB.
- To study of the effect of interaction at the interface between fibres and cement hydrates and also between natural fibre and synthetic fibre in FCB.
- To find an appropriate method to manufacture the specimens in the laboratory based on the principle of the Hatschek process.
- To compare the results of manufactured specimens with the values of commercial cement boards.

1.4 Methodology of research

The methodology used in this research is based on experimental laboratory tests that have been carried out during the past five years. The research focuses on the use of discrete and randomly oriented fibres mixed with cement and water. As the first step, some of the chemical and mechanical properties for some different organic and inorganic fibres such as resistance to alkaline and tensile strength were studied. Then a special casting setup based on a vacuum dewatering system was designed and made to produce similar cement boards in the laboratory. Over seventy mixes with different fibre proportion, additives and admixtures were designed, made and tested. After analysing the results, the optimum mix design was identified. Scanning electron microscopic studies were also carried out to clarify the microstructures of composites for some selective specimens. Some of the most important mechanical and physical properties were measured according to relevant standards in the laboratory. The final stage of the research was to try to adapt the laboratory scale process into an industrial

scale process by conducting factory site trials. Then the results were compared to the values of commercial cement boards available in the market.

1.4.1 Overall research steps and details

The research steps taken are summarized as follows:

1. Conducting literature review.
2. Visiting FCB factories.
3. Designing and building equipments to simulate the Hatschek process in the laboratory based on the vacuum dewatering procedure.
4. Choosing several types of waste natural fibres such as bagasse, wheat, eucalyptus and cardboard based on the literature review and by analysing the characteristics of fibres.
5. Identifying the most important characteristics of fibres such as length, diameter, tensile strength; scanning electron microscopy was also done to study the microstructure of fibres, particularly the surface properties.
6. Making many trial specimens (≈ 50) with designated moulds to find a suitable proportion of cement, water and fibres, and other adjustments of procedure such as vacuum power, mixing time, finding a suitable blade for mixing and the appropriate speed for the mixer.
7. Up to this stage, all required equipment, materials and knowledge of how to make fibre cement board in the laboratory were achieved. Hereafter manufacturing of specimens was begun in order to study the effects of different parameter on the cement board characteristics, including:

a. Experimental studies to understand the effect of fibre length and aspect ratio.
b. Flexural strength tests according to relevant standards.
c. Making many mixes to find the optimum percentage of the kraft fibres proportion (1% up to 14%).
d. Analysing the results and choosing the kraft fibres as the primary fibres (reference specimens reinforced by the kraft fibres solely for the rest of the mixture design).
e. Analysing the results of the mixes made with kraft fibres.
f. Optimization of mix proportion for specimens reinforced by kraft fibres to get the highest flexural strength.

8. Evaluating different cheap and available synthetic fibres such as glass, steel, acrylic, polypropylene and nylon. Acrylic and polypropylene were selected for further study.
9. Making specimens with different percentages of 3 mm and 6 mm length polypropylene fibres and testing flexural performance.
10. Making specimens with different percentages of 5 mm length acrylic fibres and testing flexural performance.
11. Choosing acrylic fibres as suitable synthetic fibres for further study.
12. Optimizing mixes containing acrylic and kraft fibres to get the highest flexural strength.

13. For some selected mix designs which were obtained at the previous stages, examining the effect of replacing different percentages of silica fume for cement on flexural performance.
14. For some selected mix designs which were obtained at the previous stages, examining the effect of replacing different percentages of limestone powder for cement on flexural performance.
15. For some selected mix designs which were obtained at the previous stages, examining the effect of replacing different percentages of combination of limestone powder and silica fume for cement on flexural performance.
16. At this stage, the mixes that showed the highest flexural strength were determined. Theses mixes were selected for physical tests such as density, moisture movement, water absorption and moisture content.
17. Choosing three mixes out of previous mixes that had the highest flexural strength and appropriate physical characteristics for freeze-thaw testing.
18. Selecting two out of three mixes, which satisfied relevant standards and showed the best characteristics in mechanical, physical and durability, as trial mixes for the factory.
19. Adapting the laboratory scale process to an industrial scale process.
20. Successfully manufacturing full-scale cement board in the factory.
21. Analysing the results of pilot test specimens.

1.5 Layout of thesis

This report includes seven chapters as follows:

In the first chapter, a brief description of all conducted research works is presented and illustrated for readers, particularly the objectives and methodology of the research.

In the second chapter, some relevant literature, on which this research is based, is presented. In this chapter, at first much attention is focused on the characteristics of asbestos fibres because the aim of this research is to find alternatives for asbestos in fibre cement board, so understanding and identifying asbestos characteristics and its performance in fibre cement should be studied. The available scientific references such as journal papers and research reports on using asbestos fibres in cement composite goes back to 1960, so some of the references for this chapter are from 1960 - 1985 because, after people began to understand the hazard of asbestos to human health, the research on the application of asbestos in cement composite was ceased. However, the rest of this chapter includes the results of recent studies on applications of natural and synthetic fibres in cement composites.

In the third chapter, the materials and fibres used in this research are introduced. Also, the results of some of the most important tests that are commonly conducted on the materials and fibres to identify their characteristics are presented.

In the fourth chapter, the following issues were addressed: designing and making the mould to produce specimens in the laboratory, the governing concepts of mix design and proportion of ingredients, introducing the methods for physical, mechanical and durability tests on specimens.

In the fifth chapter, the results of the conducted tests are presented, analysed and discussed.

In the sixth chapter, the results of the laboratory tests are generalized to industry so that, based on the outcome of the whole research up to this stage, two of the best mixes were selected and several trial full-scale cement boards were manufactured in a factory.

In the seventh chapter, a summary of all outcomes of this research along with suggestions for future research are presented.

Chapter 2: Literature review

2.1 Introduction

The idea of using of fibres to improve material which is weaker in tension than in compression has been done many years ago. Probably the oldest written account of such a composite material occurs in Exodus i.e. straw was used to reinforce clay bricks. At that time period (approx 3500 years ago) , straw was used for reinforcing sun backed bricks to build the 57 m high hill of 'Aqar Quf' close to Baghdad city (Swamy 1980, Bentur et al. 2007).

In modern time, in 1903, the first broadly used manufactured construction materials composite was invented to produce asbestos cement composite using the ‘Hatschek’ process. To make asbestos cement composite using paper-making production equipment was invented by Ludwig Hatschek and is named after him. Nowadays, various kinds of fibres are used to reinforce different materials such as epoxies, plastics and cement tiles. In this thesis, we will concentrate on the use of fibre reinforcement in materials made with hydraulic cement binders.

In this context, we will define *fibre reinforced cement* as a material made out of cement and discrete fibres (but containing no aggregate). *Fibre reinforced concrete* is made with hydraulic cement, aggregates of various size (typically 20 mm), incorporating discrete, discontinuous fibres. So, we will use the term FCB (Fibre Cement Board) as a general class of composite boards regardless of their exact nature of the matrix (paste, mortar or concrete).

Since the early use of asbestos fibres, a wide variety of other fibres have been applied in conjunction with hydraulic cements. Conventional fibres such as glass and steel, new fibres such as Kevlar, polyvinyl alcohol, and carbon or; and spread range of other fibres, either man-made (nylon, acrylic and polypropylene,) or natural (wood, agricultural waste, cellulose). These fibres are different in properties, cost and effectiveness.

Some common fibres along with their typical properties are illustrated in Table 2-1. In addition to their mechanical properties, fibres also vary largely in their geometry. The use of steel and glass fibres in the early work on FCB in the 1950s and 1960s were smooth and straight.

Since then, however, more complicated geometries have been developed, mostly to amend their mechanical bonding with the cementitious materials.

Thus, modern fibres may produce in different profiled shapes, hooked or deformed ends. They may occur as fibrillated films or bundled filaments, or they may be used as woven fabrics or mats.

Unreinforced fibre cement boards have low tensile strengths. Thus, they are classified as *brittle* materials. Therefore, they need to be *reinforced* before they can be used as building materials.

Table 2-1 Typical Properties of Fibres (Bentur 2007)

Fibre	***Diameter (μm)***	***Specific gravity***	***Modulus of elasticity (GPa)***	***Tensile strength (GPa)***	***Elongation at break (%)***
Steel	5-500	7.84	200	0.5-2.5	0.5-3.5
Glass	9-15	2.60	70-80	2-4	2-3.5
Asbestos:					
Crocidolite	0.02-0.4	3.4	196	3.5	2.0-3.0
Chrysotile	0.02-0.4	2.6	164	3.1	2.0-3.0
Fibrillated Polypropylene	20-200	0.9	5-77	0.5-0.75	8.0
Aramid (Kevlar)	10	1.45	65-133	3.6	2.1-4.0
Carbon (hifg strength)	9	1.90	230	2.6	1.0
Nylon	-	1.1	4.0	0.9	13.0-15.0
Cellulose	-	1.2	10	0.3-0.5	-
Acrylic	18	1.18	14-19.5	0.4-1.0	3
Polyethylene	-	0.95	0.3	0.7 10^{-3}	10
Wood fibre	-	1.5	71.0	0.9	-
Sisal	10-50	1.50	-	0.8	3.0

In the past, this reinforcement has been in the form of continuous reinforcing steel bars which could be placed in an appropriate locations in the structure to withstand the imposed tensile and shear stresses. Another method which was applied to reinforce

building materials particularly fibre cement was fibres which are usually discontinuous and randomly distributed in the cement composite. Therefore, it is not expected that they are ideal in withstanding tensile stresses. However, since they are close to each other rather than conventional reinforcing bars they have better function in controlling cracks. Therefore, conventional reinforcing steel bars which are suitable to be used in concrete could increase the load bearing capacity of concrete while randomly discrete fibres are more effective for controlling the cracks.

As a result of these differences, there are certain applications in which fibre reinforcement has better function than conventional reinforcing bars. These include:

Thin sheet cement board, so that conventional reinforcing bars cannot be used. In thin sheet materials, fibre content is relatively high. Normally greater than 5% by volume. In these applications the fibres increase both the tensile strength and the toughness of the composite, as observed in Fig. 2-1.

Products which must resist locally high deformations or loads such as blast resistance structures, tunnel linings or precast piles which must be hammered into the ground and must have high toughness and ductility.

Components in which fibres are used to control the cracks induced by temperature variations or humidity such as pavements and slabs. In these applications, fibres which are very smaller than rebar are preferred to use as crack arresters.

Figure 2-1Typical stress-strain curves for low fibre volume and high fibre volume FCB. (Bentur 2007)

In the second application, the aim of using fibres is not to enhance the strength of concrete. However, as a result of using fibres a relative improvement in strength is observed. As observed in figure 2-1, the use of fibres in cement composites largely controls cracking. This could increase other strength properties such as fracture toughness (energy absorption capacity) and ductility.

Adding fibres can also lead to an improvement in abrasion resistance, impact resistance, fatigue characteristics as reported by Bentur (2007).

The production technologies to produce fibre cement boards that are currently available (Coutts 2005, Bentur 2007) may be classified as follows,

Premix process: In this method, the fibres are blended with the cementitious matrix in a mixer. They are treated as an extra ingredient in the most common method of producing a cementitious mix. However, the fibres reduce the workability. Only about 2% of steel fibres and only a few tenths of a percent of polypropylene fibres can be introduced in the mix by this method.

Spray-up process: This technique is used primarily for cement composite reinforced by discrete glass fibres. At the same time, cement slurry and discrete glass fibres are sprayed onto the forming surface to produce thin sheets. In this method, high fibre volumes of up to about 6% can be used.

Shotcreting: With the use of particular equipments, steel fibre in conjunction with cementitious materials could shotcrete on any types of surface. This method often used for stabilization of rock slopes and lining of tunnels. In this method also, relatively high volumes of fibres can be added to the mix.

*Pulp Type Process*es: For asbestos cement boards (or when cellulose or other fibres are used as an alternative for the asbestos) the fibres are distributed throughout the slurry, they are then dewatered to produce fibre cement board. These can be built up to the required thicknesses by layering. In this method, fibre content is normally between 10 - 20% by the cement weight.

Hand Lay Up: In this method, layers of fibres in the form of net or mats are placed in moulds, impregnated with cement slurry and then vibrated or compressed to produce dense products. In this method, high value of fibre content (up to 30% by volume) can be used.

Continuous Production Process: Continuous fibres mats and fabrics can be impregnated with cement slurry by passing them through a cement bath in a continuous process. The impregnated fibres or the thin sheets can then be wound on a suitable mandrel and pressed, to achieve fibre volumes in excess of 15%.

A brief classification of conventional and modern methods to produce FCB base on aforementioned are demonstrated in table 2-2.

Table 2-2 Typical methods to product FCB (Bentur 2007)

At the end of this section, it should be noted that as mentioned in table 2-2, there are several methods to produce the cement boards which are different in fibre processing and manufacturing procedures. The characteristics of fibres, cementitious materials and method of manufacturing specimens affect the characteristics of final products. Therefore, the evaluation of the reinforcing effects should be determined by testing

cement board made in a full scale Hatschek process or pilot plant or specimens prepared in the laboratory by a simulation process involving preparation of a slurry followed by vacuum-dewatering in combination with pressing.

2.2 Fibre reinforced composite structure

The properties of fibre reinforced cement composite are dependent on the structure of the composite. Therefore, in order to analyze these composites and to predict their performance in various loading conditions their structure must be studied. The three aspects that must be considered are:

2.2.1 Cement matrix

The bulk cementitious matrix is similar to other cementitious materials and it can be affected by the properties of filler particularly pozzolanic materials such as silica fume.

2.2.2 Fibres function

Many types of fibres which are different in physical, mechanical, and chemical characteristics have been studied and used for reinforcement of cement composite, as mentioned in table 2-1. There are two important geometrical properties which may affect the function of fibres in composite.

(1) The shapes of the individual fibres

(2) Their dispersion on the cementitious matrices (Fig. 2-2).

The individual fibres may be subdivided into two groups: discrete monofilaments separated one from the other; and fibre assemblies, typically made out of bundles of filaments, each with a diameter of ~ 10 μm or less.

Figure 2-2 Classification of fibre arrangements in 1, 2 and 3 dimensions and as continuous (a,c) or discrete, short fibres (b,d). (H.G. 1971)

(a) 1-Dimensional arrangement; (b,c) 2- Dimensional arrangement; (d) 3- Dimensional arrangement.

The bundled structure is typically made of many man-made fibres. Whether inorganic (e.g., glass, Fig. 2-3) or organic (e.g. carbon, Kevlar) and it also shows up in some natural fibres. (e.g. asbestos).

There are two distinctly different types of fibre reinforcing arrays,

(a) *Continuous reinforcement*, in the form of long fibres which are incorporated in the matrix by techniques such as filament winding or by the lay-up of layers of fibre mats and

(b) *Discrete, short fibres*, usually less than 50 mm long, which are incorporated in the matrix by methods such as spraying and mixing. The reinforcing array can be further classified according to the dispersion of the fibres in the matrix as 1-, 2- or 3-dimensional (Fig.2-2).

When the fibres are used in the continuous form, they can be aligned in a preferred orientation which is controlled by the manufacturing process (orientation of winding, or lay-up direction of the mat) and the structure of the mat.

Figure 2-3 The bundled structure of glass filaments (Bentur 1987)

A 2-dimensional distribution may also be promoted in thick cement composites using vibration.

The volumetric distribution of the fibres is extremely dependant on the mixing and consolidation process and in practice a uniform distribution of fibres throughout the volume of matrix is rarely achieved.

(Fig. 2-4). The analytical treatment of fibre distribution can be based on various stereological models (Bentur 2007).

Figure 2-4 Non- uniform distribution of steel fibres in concrete observed by X-ray, (Bentur 2007)

2.2.3 Interface of fibre-cement

Fibre cement board is usually characterized by a transition zone in the vicinity of the reinforcing inclusion so that the microstructure of the composite is significantly different from that of the bulk cement matrix away from the interface. The nature and size of the transition zone are dependent on the type of fibre and the manufacturing

technology. In some cases, it can change significantly with time. These characteristics of the fibre-cement interfacial zone exert several effects on properties of composite particularly fibre-cement bond and the debonding process across the interface.

The special microstructure of the transition zone in cementitious composites is closely related to the particulate nature of the matrix. The matrix consists of discrete cement particles ranging in diameter from ~ 1 to ~ 100 μm (average size of ~ 10 μm) in the fresh mix which on hydration react to form mainly colloidal CSH particles and larger crystals of CH (Bentur 2007). The particulate nature of the fresh mix exerts an important influence on the transition zone as it leads to formation of water-filled spaces around the fibres due to two related effects:

Bleeding and entrapment of water around the fibres inclusion; and

Incompetent packing of the ~ 10 μm cement grains in the 20-40 μm zone around the fibre surface.

Thus, in the vicinity of the fibre the matrix is more porous than the bulk paste matrix and this is reflected in the development of the microstructure. As hydration advances, the initially water-filled transition zone does not develop the dense microstructure typical of the bulk matrix and a considerable volume of CH crystals tend to deposit in large cavities, Fig 2-5.

When the microstructures in the transition zone are studied, a differentiation should be made between bundled filaments (e.g. glass) and discrete monofilament fibres separated from one to another (e.g. steel). The whole surface of the Monofilament fibres can be in direct contact with the matrix whereas in the bundled filaments only the externals filaments have direct access to the matrix.

Figure 2-5 Schematic description of the transition zone in steel fibre reinforced cement (Bentur 2007)

An investigation was carried out by Savastano et al (2005) on microstructure of cement composites reinforces by waste fibres such as sisal, banana and eucalyptus.

In addition to SEM (Scanning electron microscope), they used BSE technique (Back scattered electron) to observe cut and polished surfaces. A BSE image permits easy identification of composite phases by way of atomic number contrast. The BSE imaging is applied to study the fibre–matrix transition zone (Savastano et al. 1999).

They showed that as a result of high capacity of water absorption (~100% by mass) of sisal slivers, the water-cement ratio in the vicinity of the fibres increases. Then the differential drying shrinkage for cement and fibres generate cracks close to the fibre–cement interface as depicted in Fig 2-6.

Figure 2-6 BSE of sisal sliver in cement matrix (Savastano et al. 1999)

Figure 2-7 SEM of sisal sliver in cement matrix (Savastano et al. 1999)

In Fig 2-6, dark grey phases shows sisal slivers and medium grey area shows hydration products and denser un-hydrated cement is illustrated by light grey. As the slivers shrunk strongly upon drying de-bonding occurs so that cracks are observed close to the fibres due to internal tensile stresses generated by changes in volume of fibres.

Fig. 2-7 shows individual sisal fibres in bundles shape which have low contact area within matrix. Aspect ratio of these fibres was 89 which limited length of anchorage. This led to fibre pullout becomes the most important reason of fracture. Also, they reported that as a result of high stiffness of slivers, dispersion within the matrix is difficult.

Base on that research, maximum fibre content for sisal sliver is 4% by weight while kraft pulped fibres are able to be introduced up to 14% content.

In contrast to the sisal sliver, kraft pulped sisal fibres demonstrated better contact area within cement matrix performing total fibre perimeter about 10 times larger than the corresponding slivers. Higher magnification of the sisal kraft fibre is shown in Fig. 2-8b.

The circle shape cross-section of individual filaments and/or the open internal lumen are characteristics of kraft pulp fibres.

Figure 2-8 BSE of sisal kraft fibre in cement matrix (Savastano et al. 1999)

As can be seen in Fig. 2-8, there is good bonding in fibre–cement interfacial areas however partial fibre de-bonding similar to Fig. 2-6 (BSE sisal slivers in cement matrix) is also observed. Savastano et al (2005) showed no calcium hydroxide rich transition zones were identified by spot analyses close to the fibres.

They concluded that elevated stiffness, volume change in wet-dry cycle and low specific contact area with matrix are negative factors for slivers as reinforcement of cement. Also slivers comprise bundles of fibres that are lignin-rich resulting decomposition in highly alkaline cement matrix.

2.3 Asbestos fibre cement composite

Asbestos cement was the first fibre cement board in modern times, and is still produced by many factories. Asbestos fibres are made of natural crystalline fibrous minerals comprising bundles of filaments (fibrils) with individual filaments being as thin as 0.1 μm or even less (Wiliden 1986).

The success of asbestos-cement was due to compatibility between the fibres and the cement matrix. Asbestos bundles tend to be split up during the processing procedure, and this increase lateral surface area which is important for increasing bonding in fibre-cement interfacial.

In addition, other characteristics such as high modulus of elasticity ,high tensile strength, and to their consistency with the cement, provide uniform dispersion of fibre and finally enhances the fibre-matrix bond in the hardened composite (Wiliden 1986).

2.3.1 Production process

The technologies of production cement board (Wiliden 1986) are based on the preparation of asbestos-cement-water slurry, and the subsequent formation of a thin lamina of the de-watered slurry. Frequently, the build-up of the layered laminate is obtained by continuous winding of the lamina onto a cylinder (mandrel). The final product can be formed as a pipe, flat or corrugated sheet. The final production stage is curing, which can be usually conducted at room temperature.

The most common manufacturing method to produce asbestos-cement composite is the Hatschek process. A schematic description of a Hatschek machine is presented in Fig. 2-9 five stages of production can be identified:

1. Slurry preparation (not shown in Fig 2-9).
2. Lamina formation on the sieve cylinder (1 in Fig. 2-9) and its continuous application on the running felt (3 and 12 in Fig. 2-9).
3. Build-up of the lamina (layers) into a laminate by winding on the cylinder (mandrel), until the required thickness is obtained (7 in Fig. 2-9).
4. Cutting and shaping if required (8 in Fig. 2-9).
5. Curing (not shown in Fig. 2-9).
6. The critical step in the process is the formation of the lamina; at this stage the asbestos fibres play a critical role.

1. Slurry vats	5. Vacuum box	9. Take-off conveyer
2. Sieve cylinders	6. Breast roll	10. Whipper
3. Running felt	7. Formation cylinder	11. Suction box (felt drying)
4. Couch rolls	8. Cutting wire	12. Lamina

Figure 2-9 Schematic description of the Hatschek process (wiliden 1986)

As the sieve cylinder rotates, a slurry layer is deposited on its surface, which turns into a coherent layer as water filters from it into the 'dry' side of the sieve cylinder where some back-up water accumulates. The properties of the laminate depend upon the filtration rate.

An additional important aspect of the deposition of the slurry on the sieve cylinder and of the lamina formation is the phenomenon of streaming of the deposited slurry. This may lead to a preferred orientation of the fibres. This effect which is usually detrimental

to the performance of the hardened composite is enhanced by high speed and by the presence of longer fibres.

After adequate lamina formation and deposition on the running felt, water content in the lamina has to be controlled in order to facilitate the successful completion of the imminent production stages. Optimum water-cement ratio in Hatschek process is 35-40%. This value could provide sufficient plasticity for corrugating the specimens without cracking or deformation of paste to produce fibre cement pipes.

Water-cement ratio in slurry is about 3.5. When a thin layer of lamina is formed on running felt, the W/C ratio reaches to 0.60. In this stage, vacuum pumps which are placed along the running felt drain the excess water and the water/cement ratio reaches to 0.34- 0.36.

The filtering characteristics are important when de-watering process is doing on the lamina. Poor filtration slows down the process to extend the residence time over the vacuum boxes.

The final stage of the manufacturing process is curing where in the specimens are kept in a tunnel 70-80◦C for about 8-10 hours and then left outside for air-curing for roughly around 28 days.

Fibres have two functions in fibre cement board manufactured in Hatschek process.

- Process fibres (generally cellulose) create the right rheology and entrap the fine particles of cement and fillers when the slurry passes through the sieve.
- Reinforcement fibres (generally PVA fibres) which are longer than cellulose fibres and contribute most to strength and physical performance.

In asbestos cement board, asbestos fibres with different size perform both functions.

2.3.2 Properties of asbestos -cement composite

Asbestos is the collective name given to a variety of naturally occurring fibrous silicates which are crystalline in structure. Depending on their mineralogical composition, they can be subdivided into two main categories;

- Serpentine
  - Chrysotile
- amphibole
  - Amosite
  - Crocidolite
  - Tremolite
  - Actinolite
  - Anthophyllite

Some of the most common characteristics for three important types of asbestos fibre are presented in Table 2-3.

Table 2-3 Physical properties of some varieties of asbestos (Hodgson 1979)

Property	**Chrysotile**	**Amosite**	**Crocidolite**
Tensile strength (MPa)	3100	2500	3500
Young modulus (GPa)	160	160	190
Flexibility	Good	Fair	Good
Specific gravity (gr/cm^3)	2.6	3.4	3.4
Fibre diameter (µm)	0.03-100	-	0.5
Fibre length (mm)	1-5	-	< 5
Surface area (m^2/g)	10	-	-

The common average diameter of the asbestos fibre is in the range of 0.02 to 0.2 μm, (Hodgson 1979). In fact, asbestos fibres consist of bundles of fibrils so that they are split up during processing. Before using asbestos in the Hatschek process, splitting of the fibre bundles (fibrillation) is carried out by mechanical milling. The fibres are then introduced to the slurry preparation stage.

Different types of asbestos can be used in cement board depending on the properties such as length and degree of fibrillation. These characteristics determine the effective aspect ratio which is important in controlling the properties of the composite, both in the processing stage as well as the reinforcing.

The crystalline structure of the asbestos is characterized by a stable silicon-oxygen structure. Theoretically, could lead to a considerable tensile strength of 10 GPa (Hodgson 1979). In practice, the measured tensile strength is about (300 to 4000 MPa (Table 2-4). This value is dependent on the asbestos type, testing method and specimen preparation and is considerably lower than the theoretical.

The bundled structure of the asbestos fibre has an important effect on lateral surface area which depends on the degree of fibrillation obtained during their processing.

Typical surface areas after milling as measured by N_2 adsorption are approximately 3000m^2/kg (Hodgson 1979). This is about 5 times the area prior to milling, and about 10 times the area of ordinary Portland cement.

Fibres length is an important parameter in flexural strength and product processing. Longer fibres could have a favourable effect on flexural strength. However, fibrillation processing causes some degradation in fibre properties such as fibre shortening and the fines generation. Therefore, processing has two effects: increases the surface area,

which is a favourable effect but at the same time it reduces length which is detrimental. Consequently, finding maximum strength needs optimum processing time and intensity of milling (Fig. 2-10). In addition, the filterability reduces continuously with progressive processing.

Table 2-4 Strength and Modulus of Elasticity of Asbestos Fibres (Hodgson 1979)

Fibre type	**Tensile strength (MPa)**	**Modulus of elasticity (GPa)**
Chrysotile	3000-3200	160
Crocidolite	3000-4000	180-200
Amosite	2400-2500	160
Tremolite	310	152
Actinolite	1890	146
Anthophylite	1350	154

Figure 2-10 Effect of processing on length, surface area and strengthening in the hardened composite (Wiliden 1986)

Asbestos-cement factories prefer to use a blend of different types of asbestos fibres to optimize the properties of the mix in the processing stage and strength of hardened composite. In other words, some of the asbestos fibres are selected for their processing characteristics while others are used for enhancing the flexural strength.

2-3-2-1 Mechanical properties of asbestos-cement composites

H.G (1971) and Akers et al (1983) showed that the mechanical properties of the composite are controlled by the processing parameters and the composition of the hardened composite. It should be noted that flexural strength and modulus of elasticity are two important mechanical parameters that are affected by fibre content and fibre length. Akers et al (1986) proved that maximum flexural strength gain at intermediate fibre content while with increasing fibre content the modulus of elasticity decreases (Fig. 2-11 and Table 2-5).

Table 2-5 Effect of fibre content on properties of Asbestos-Cement Composites (H.G. 1971)

Asbestos fibre could change its function in the cement matrix when treated, so that fibrillation of fibres by mechanical milling could break the bundle structure.

A: low fibre content; B: high fibre content; C: intermediate fibre content.

Figure 2-11 Stress-strain curves of asbestos-cement composites with different fibre contents (H.G 1971).

Allen (1971) was of the opinion that fibrillation and milling improves the properties of the cement composite which when compared to the fibres are used in the same form as received from the mine (Table 2-6).

Table 2-6 Effect of fibre processing on the properties of Asbestos-Cement Composites (H.G. 1971)

2.3.3 Microstructure of Asbestos - cement Composite

SEM characterization of the fractured surface of asbestos-cement composites was reported by Akers and Garrett (1983). It was shown that in the cement composite many of the asbestos fibres are in the form of bundles. (Fig. 2-12)

The diameter of asbestos fibres is between the range of <1 μm and .02 μm. The fibre length is between 0.7 mm and 5 mm. The average aspect ratios of fibres would be greater than700 . Akers and Garrett (1983) found that there are two important mechanisms of fracture for asbestos cement board when it is subjected to flexural strength test. These mechanisms are fibre snapping and pull-out.

They attributed these mechanisms to a complex combination of fibrillated fibres bundled structure of the asbestos fibre and fibre-cement interfacial zone.

Figure 2-12 The bundled nature of the fibre in an asbestos-cement composite, (Akers et al. 1983)

They showed that in many types of cement composites there is a weak interfacial transition zone which is rich in CH. While in the asbestos cement composite that weak zone is not found and in spite of other composite which is rich in CH. In asbestos cement board, the interfacial zones, Ca/Si ratio is the same as that of the bulk (≈ 2:1) and no evidence of accumulation of CH is observed. This was proved by observations of broken samples so that after fibre pull-out cement had been attached to the surface of the pulled-out fibre. It shows a strong interfacial zone and de-bonding away from the interface in the matrix. The increase in cement-fibre interfacial bonding is due to the densification of the interfacial microstructure of the matrix which is related to the high

hydrophilic surface of the asbestos fibres compared to other fibres and also to the processing of the asbestos-cement composites. This is probably the reason why it omits the tendency of formation of water-filled spaces around the fibres in the fresh product.

2.4 Asbestos Banning

After understanding asbestos hazard on human health, in the early 1970s a global movement was established to remove asbestos fibres from a wide range of products. Asbestos- cement board was a main user of asbestos (Coutts 2005).

Studies show asbestos is a hazard when tiny particles are inhaled and deposited within the lungs (Bassani et al. 2007 and Shih et al. 1995). Several illnesses may occur due to asbestos fibres. They are Asbestosis, lung cancer and Mesothelioma (Marty 2011, Niklinski et al 2004).

Also, studies (Bassani et al. 2007, Shih et al. 1995) showed that people who are persistently exposed to high levels of airborne asbestos in the work environments such as construction, manufacturing, shipbuilding, mining, milling etc are at a higher risk.

Although, sealed and undisturbed asbestos cement composites are not a hazard, residents of buildings made of asbestos materials are in a risk to their health, as weathering of the asbestos cement sheet leads to asbestos fibres becoming airborne and are consequently inhaled (Bassani et al. 2007).

Those countries that understood the need to legislate the law against the use of asbestos on health grounds have achieved most advance techniques with respect to asbestos alternatives.

The first country in the world was Australia to be totally free of asbestos in fibre cement composites in 1982. Other countries, particularly European Union prohibited

asbestos by 1995. For example, Norway, Sweden, and Denmark eliminated the use of asbestos by 1987. In 1989 the governments of Italy, Netherlands, Switzerland and Belgium had banned the use of asbestos (Coutts 2005).

Countries such as Russia and China are involved in more than half of the world's asbestos production and also users of asbestos fibre in cement composites. This trend is expected to continue for some time into the future. Even though some research is being carried out into non-asbestos composites there is no strong movement observed towards banning asbestos usage in these countries (Coutts 2005).

Based on a report of Agency for Toxic Substances and Disease Registry (ATSDR 2004), the diameter of a fibre is an important property because very thin fibres are more easily suspended in air than thick fibres and they can be inhaled in and deposited deep into the lungs. Only very thin fibres with diameters less than 3 μm are able to reach into the lower respiratory tract of humans. Thicker fibres are deposited on the surface of the upper respiratory tract which includes the nose and mouth. The World Health Organization (WHO) counts breathable fibres as particles with lengths greater than 5 μm and diameters less than 3 μm, and aspect ratios ≥3.

2.5 Natural fibre as asbestos replacement

The characteristics of asbestos fibre are unique. Some of these properties are

- Control of the properties of the slurry.
- Ability for dewatering techniques.
- Providing an excellent reinforcing efficiency in the hardened composite.
- High strength and modulus of elasticity.
- Appropriate bonding within cement matrix.
- Good stability in the alkaline cement media.
- Providing an excellent durability for composite.

This combination of properties is difficult to be observed with any other type of fibre in the world.

Normally, there are some fibres which could match the mechanical properties of asbestos, but they cannot provide all required aforementioned characteristics in the Hatscheck process.

Jamshidi et al (2011) studied acrylic and glass short fibres in separate and hybrid forms as an alternative for substituting asbestos in the Hatscheck process.

They reported that an appropriate ductility and strength were obtained for the sheets containing glass fibres and these characteristics were better when a hybrid of acrylic and glass fibres was applied.

They found that glass fibres cover only some of required properties such as proper mechanical characteristics but as a result of poor adhesion to the cement, these fibres are not recommended to be used solely in FCB.

The idea that seems to be pursued at present is to develop an alternative made up of a blend of different types of fibres so that some of them function as 'processing fibres' while the others are applied to reinforce the composite.

The processing fibres are required to enable homogeneous dispersion in the slurry and to provide good filtering characteristics and also solids retention. Such fibres must have high surface area and web forming properties.

Many research works showed that cellulose fibres have suitable potential for this goal. This will be discussed in detail later in this thesis. On the other hand reinforcing fibres should possess sufficient mechanical characteristics (strength, modulus of elasticity, bond) as well as stability in an alkaline environment.

At present, there are two important alternatives for asbestos which are used in most cement board factories,

- Cement board reinforced by “Wood and cellulose fibres”.
- Cement board reinforced by “combination of synthetic and cellulose fibres”.

2.5.1 Wood and cellulose fibres

In recent years much of the research concentrated on the use of natural fibres which are accessible and cheap combined with easy production processes for making cement boards which are suitable for low cast housing applications. This subject is reviewed in several references.

Wood Strand Cement Board (WSCB), a class of recently-developed panels composed of long and thin wood strands bonded with Portland cement has appropriate resistance to severe weathering, fungal growth, and insect attack. WSCB panels exhibit good durability, structural strength, resistance to fire, and high resistance to rot, fungal decay,

and attack by termites and other vermin. Further, they are easily nailable, exhibit excellent screw-holding capacity, and can be easily painted and stuccoed. Also, because WSCB panels adhere strongly to fresh concrete; they can be used for permanent shuttering of concrete walls, pillars, and floors, such as those found in basements (Aro 2008).

Many studies have demonstrated that cellulose fibres can be considered as one of the candidates for asbestos fibre in cement composite using the Hatscheck process due to the individual properties, accessibility and economic aspects (Savastano et al. 2001, Savastano et al.2003, Agopyan et al.2005).

Much effort has been devoted to wood fibres because they possess many advantages such as availability, lower cost, simple production processes for making cementitious composites of various shapes, renewability and recyclability, non-hazardous nature, and biodegradability. (Bentur 2007)

Many types of fibres have been used or have been studied to be used as reinforcement for cement board and they include coconut, bagasse, sisal, wood chips, bamboo, palm, elephant grass, jute, flax, akwara, plantain and water reed. It is beyond the scope of this thesis to deal with the cement board with each of these fibres. Instead, only the properties and characteristics of a few systems which are representative of this class of composites will be discussed.

Also, the properties for each type of cellulose fibres can be different in each country depending on the weather, type of soil, type of fertilizers etc. So the results of each research may be exclusive and cannot be generalized to other research.

Karade et al (2010) depicted that cellulose fibres have many advantages such as low cost, availability, chemical stability, environmental friendly and reinforcing characteristics but their durability shortcomings have to be remedied. They tried to use lignocellulosic wastes fibres to manufacture FCB. However, in this effort there are various restraints like compatibility of these wastes with cement and limited composite strength.

Native fibre named Fique fibre or Cabuya was studied in connection with cementitious matrix by Delvasto et al (2010). In that research, an appropriate low scale production technology for manufacturing corrugated sheets which can be used for roofing were developed. However, the result of this experience showed that it is necessary to do some adjustments in order to overcome problems related to the parameters of the process and the type and volume fraction of the ingredients of mix.

Mechanical, physical and thermal performance of the roofing tiles produced with several formulations of cement-based matrices reinforced with sisal and eucalyptus fibres has been investigated by Tonoli et al (2011). The results showed that the physical properties of the tiles were more influenced by the fibre content of the composite than by the type of these processing fibres. According to the results of that study, after approximately four months of age under outside weathering the toughness of the vegetable cement composite fell to 53– 68% of the initial toughness at 28 days.

Karade et al (2010) concentrated on lignocellulosic wastes which are generated worldwide from various sources such as agriculture, construction, wood and furniture to make cement-bonded construction materials. They faced various restraints like compatibility of these wastes with cement their toxicity and limited composite strength.

To overcome these drawbacks, they had to take some requirements such as pre-treatments use of chemical admixtures and modified manufacturing process.

Khorami et al (2011) studied three types of cement board reinforced by waste natural-sourced fibres: wheat fibre , bagasse fibre and eucalyptus fibre. For each group, 2 and 4% fibre content by the cement weight were investigated.

The results showed that the flexural performance of the cement boards depends on the type, length, diameter, aspect ratio and texture of fibres. Also for all groups with increasing fibre content from 2 to 4 percent of cement weight, flexural strength increases. They also showed that the highest flexural strength belongs to the cement board reinforced by bagasse.

Wood (cellulose) fibres are inflexible and short but are usually sturdy and perform better in long term in the cement board. Wood chips are processed in different solutions and subjected to mechanical treatment to obtain good quality. Cellulose-pulp fibres can be used as reinforcement in cement composites particularly in the Hatschek process.

The fibre content could be as high as 10% or even more. Meanwhile, these fibres may be applied for full or partial asbestos alternative. Many cement board reinforced by different percentage (2, 4, 6, 8, 10, 12 and 14%) of kraft pulp fibres obtained from waste cardboard were made and subjected to flexural test (Khalilitabas et al 2009). The results showed that by increasing the fibre content up to 8% by the cement weight, the flexural strength and toughness increased. Increasing fibre content greater than 8% by the cement weight just increases toughness and decreases flexural strength.

As aforementioned studies show, agricultural waste fibres which are broadly accessible in most developing countries have been drawn the attention of research as an

appropriate fibres to reinforce cement matrix particularly in the last decade. The most important question may arise in mind is “Why there are many differences within different types of cellulose fibres so that some of them have better characteristics?”

Different fibres have different microstructure which is quite complex. As wood is a product of biological growth, it is variable in composition. However, the featured components such as lignin and polysaccharides are always present in major characteristics. Other components demonstrate greater variation.

In figure 2-13, a schematic structure of sisal fibre wall is presented. The fibre length is 2-4 mm, diameter less than 0.2 mm and there are about 100 cells in its cross-section (Bentur 2007). As can be seen, the layered fibrils make up the fibre wall and having different directions which are composed mainly of long oriented cellulose molecules. The chains of cellulose molecules are grouped in long oriented micro fibril units having a thickness of about 0.7 mm. The other components of the cell wall, namely lignin and hemi-cellulose are located mostly in the middle lamellae which connect the fibre cells together.

In the processing of pulp which natural fibres are used as asbestos alternative, many of the fibres break into the individual fibre cells. Therefore, any changes in microstructure of fibres would lead to change in mechanical and physical characteristics of fibres.

The importance of casting pressure was studied as an attempt to enhance the fibre-matrix bond in cement board reinforced by coir and Jute fibre (Das Gupta et al. 1978, Mansur et al. 1982).

(a) Cross section through sisal fibres
(b) Structure of the cellulose fibre cells (Bentur 2007)

Figure 2-13 cross section and structure of cellulose fibre

They concluded that the high initial pressure could compensate a decrease in bond which may be caused by shrinking and swelling of the fibres. The effect of pressure on the flexural strength of cement board reinforced by Jute is shown in Fig 2-14.

As observed, the optimum casting pressure of 3.1N/mm^2 can lead to a doubling of the flexural strength.

Figure 2-14 The effect of casting pressure on the flexural strength of coir fibre reinforced cement (Mansur et al. 1982)

One of the characteristics of wood fibres that may affect durability of fibre cement board reinforced by wood fibre is that it is hygroscopic in nature (Smook 2002). Dry wood is hygroscopic. It means it would readily absorb water vapour. The amount of absorption depends on the relative vapour pressure (or the relative humidity) and the temperature of the ambient atmosphere. Similarly, wet or damp wood loses water.

The absorption process is not properly reversible and as a result of hysteresis the equilibrium moisture content at specified relative moisture is higher when the condition is approached by desorption than when it is approached by adsorption. The equilibrium moisture content varies from zero in a fully dry atmosphere to about 30% (dry basis) at 100% relative humidity, i.e., the "fibre saturation point." Determining the true fibre saturation point is difficult because the isotherm rises quickly as the relative humidity

reaches to100% and small variations in temperature cause condensation or vaporization of liquid water.

Kaufmann et al (2004) showed that wood fibres are porous material containing voids and capillaries with a wide range of sizes and a large internal surface area.

They illustrated that initially water vapour is taken up as a result of surface sorption on the available internal area. The simultaneous swelling forms additional surface area as adsorption increases. As the relative humidity is increased, further sorption leads to multilayer sorption on the surfaces and condenses in capillaries with the smaller capillaries being filled first. At the fibre saturation point, all except the large capillaries are filled by water.

Wood swells as the hygroscopic moisture content is increased from dryness to the fibre saturation point and shrinks with the reverse of the process. No further swelling occurs at water contents above the fibre saturation point. The maximum external shrinkage from green to completely dry wood varies with the direction in which measurement is made. It amounts to about 4 to 14% tangentially, 2 to 8% radially, and 0.1 to 0.2% longitudinally.

The changes in mechanical properties due to moisture content are accompanied by changes in the mode of failure, with fibre pull-out seen more frequently in wet composites. The failure in the dry composites is dominated by fibre fracture with only a small extent of pull-out. The change in mechanical properties and fracture mode with moisture can be explained in terms of changes in fibre properties and the fibre-matrix bond: at lower moisture contents the fibre is stiffer and more brittle, and the bond is stronger. According to composite material theory, these two effects should lead to

higher strength and lower toughness, as observed in the dried composite. Fibre failure in the wet composite is accompanied by a reduction in cross-sectional area, and twisting and unravelling of the fibres, all of which are associated with the ductile behaviour of the wet fibres. In the dry composite there was no significant reduction in the cross sectional area of the broken fibre, and the outer layer of the fibres was stripped away rather than debonded at the interface, indicating a strong bond. The strong bond in the dry state may be the result of hydrogen bridges (Coutts et al 1984).

Tonoli et al (2010) evaluated the advantages of using hardwood short fibre pulp (eucalyptus fibres) as an alternative to softwood long fibre pulp (pinus) and polymer fibres, traditionally used in reinforcement of cement based materials. The effects of cellulose fibre length on microstructure and on mechanical performance of fibre–cement composites were evaluated before and after accelerated ageing cycles. They found out that hardwood pulp fibres were better dispersed in the cement matrix and provided higher number of fibres per unitary weight or volume in relation to softwood long fibre pulp. These reinforcing elements lead to an effective crack bridging of the weak matrix, which improves the mechanical performance of the composite after ageing.

Paki (2007) studied the potential use of limestone powder wastes and wood sawdust wastes combination for producing a lightweight composite as a building material. Various levels of those materials with different particle sizes were investigated in that research. Some of the important characteristics of the composite such as flexural strength, unit weight and water absorption values etc were tested on the specimens. The results show that application of those materials improved a sudden brittle fracture of the cement composites. In addition to high energy absorption capacity the unit weight of the composites reduced dramatically

2.5.2 Properties of wood fibres

The characteristics of the wood fibres affect the mechanical properties of wood fibre cement composites. Physical properties of wood fibre such as morphology, fibre size and surface charge are important in manufacturing processes of cement board. Similarly, the mechanical properties of wood fibres such as fracture toughness, tensile strength are important in mechanical and durability of cement board.

2.5.2.1Physical characteristics of wood fibres (Smook 2002 and Bentur 2007)

There are two important physical properties: physical dimensions and surface area

Physical dimensions

The dimensions and other related properties of typical softwood (Pinus radiata) and a typical hardwood (Eucalyptus regnans) are given in Table 2-7. Comparison of these two different types of woods shows the following differences,

(I) Softwood fibres are much longer and thicker than Hardwood fibres.

(II) Hardwood fibres usually have a higher relative cell wall thickness than softwood fibres do. This shows hardwood fibres are stiffer and have greater resistance to break.

(III) Hardwood pulps always have a large quantity of thin-walled vessels.

(IV)With softwoods there is a distinct difference between early wood and late wood.

(V) The number of hardwood fibres per unit mass is always much larger than that of softwood fibres. In one gram of pulp there may be of the order of seven or eight times as many Eucalyptus regnans as Pinus radiata fibres.

Surface area

The retention of cementitious particles by asbestos (or its alternative) and the drainage characteristics of the board during the dewatering stage are significant.

Table 2-7 Physical properties of softwood and hardwood (Bentur 2007)

2.5.2.2 Mechanical properties of wood fibres

Mechanical properties of wood fibres have an important role in both papermaker factory and cement board factory. Measuring the mechanical property of single fibre such as tensile strength is really difficult. For this reason, the information on single fibres is limited and even though in recent times developing new techniques in paper industry has been provided more data.

a. *Modulus of elasticity*- Bentur (2007) suggested that the higher limit for elasticity modulus of cellulose chain is 150 GPa. Even though the measured elasticity modulus for single fibres of softwood varies from 10-100 GPa depending upon fibril angle,

drying restraints and imperfections. As a result of defects and non-homogeneities within the structure of cell wall the practical value is much lower.

b. *Tensile strength*- Similar to elastic modulus, the tensile strength of single fibres depends on the helical angle of layers and the presence of defects. Maximum measured value of 2000 MPa for defect-free black neat fibres with a zero fibril angle, although realistic value is in the range 350-1000 MPa for particular fibre fractions carefully prepared to minimize fibre damage.

c. *Fibre flexibility*- The fibre flexibility is important during the preparation stage of a composite board and also during the process of composite failure. This property was seldom measured quantitatively. Without doubt flexibility of wet fibre is greater than dry fibres. Bentur (2007) showed that mechanical pulps are 20-30 times stiffer than chemical pulps from the same species of wood.

2.5.2.3 Durability properties of wood fibres

One of the concerns for wood fibre in cement composites is the durability of the fibres in the alkaline environment of cement. The composites may undergo a reduction in strength and toughness as a result of weakening of the fibres by a combination of alkali attack and mineralisation through the migration of hydration products to lumens and spaces. Romildo et al (2003) studied several approaches to improve the durability performance of cement boards reinforced by sisal and coconut fibres. The following methods were applied in their research:

- carbonation of the matrix in a CO2-rich environment
- the immersion of fibres in slurried silica fume prior to incorporation in the ordinary Portland cement (OPC) matrix
- partial replacement of OPC matrix by undensified silica fume

- partial replacement of OPC matrix by blast-furnace slag
- combination of fibre immersion in slurried silica fume and cement replacement

The durability of the cement board reinforced by above mentioned methods was studied by determining the effects of ageing in water, exposure to cycles of wetting and drying and open air weathering on the microstructures and flexural behaviour of the composites.

The results of their study shows that immersion of natural fibres in a silica fume slurry before their addition to cement-based composites was found to be an effective means of reducing embrittlement of the composite in the environments studied. Early cure of composites in a CO2-rich environment and the partial replacement of OPC by undensified silica fume were also efficient approaches in obtaining a composite of improved durability. The use of slag as a partial cement replacement had no effect on reducing the embrittlement of the composite.

2.5.3 Cellulose Pulp-fibre processing

The characteristics of the cellulose-pulp fibres extracted from wood depend on the method of pulping process which can be based on mechanical treatment, chemical treatment or a combination of the both. As observed in Figure 2-14, the fibre shape is cylindrical and hollow section, and its characteristics would be affected by properties of ingredients and its wall thickness.

There are three main methods to produce pulp of fibres.

2.5.3.1 Mechanical pulp

In this method, mechanical abrasion applies to separate cellulose fibres and produced fibres have more than 60% lignin (Marjatta 2004 and Ververis 2004). Thermo mechanical pulping (TMP) is normally used in this method. In TMP, metallic plates rub

steam-heated chips at high speeds to separate fibres and results un-collapsed rod shape fibre. Yield of this method is around 80-90% (Pekka 2011).

2.5.3.2 Chemical pulp

In this method, chemical reactions are used to dissolve lignin. After the removal of the lignin, the fibres separate easily. The most common method using this process is called Kraft. The yield of this method is around 40-55% and the produced fibres are normally less than 10% of the amount of lignin and results ribbon shape fibre (Marcelo et. al 2009).

2.5.3.3 Semi-chemical pulp

In this method, chemical reactions are applied to soften the lignin, then mechanical abrasion in refiners is used to produce fibres. The yield of this method depends on the baking time, amount of chemical solutions and temperature, and is between 60 and 80% (Marcelo et al., 2009).

The TMP process is conducted at a temperature greater than the transition temperature of the lignin binder and the processed fibre is coated by lignin.

In the kraft process which is the most important chemical pulping method dissolve the lignin which binds the fibre together in the wood. The chips are subjected to initial treatment with chemicals solutions in high temperature and pressure. The chemical reactions in this process are beyond the scope of this thesis.

In the kraft process many types of acidic aqueous solution (such as calcium bisulphate, sodium, magnesium or ammonium sulphites or bisulphites) are used as a pulping agent (Smook 2002).

This process could be operated under alkaline conditions too, and is applicable for all types of woods however it releases an unpleasant odour into the surrounding area.

It should be noted that the alkaline conditions cause less damage on the cellulose fibres than the acidic conditions of the sulphite process because cellulose is more easily hydrolyzed by acids than by alkalis.

In both methods, the chips are initially cooked under pressure in a solution containing the pulping agent and free sulphur dioxide. The large amount of lignin (90%) is dissolved in the solution.

The outcome of this method is a high quality cellulose fibre which could be used in paper industries or other industries such as fibre cement boards.

When the application of cellulose fibres are considered in cement board, harmful effects of certain fibre species must also be taken into consideration. The hydration and setting of the cementitious matrix may be retarded by various organic compounds like lignin and sugar in particular which are present in cellulose fibres. From this point of view, fibres produced by alkaline chemical pulping are superior compared with fibres made by the mechanical method as the hydration and setting matrix adjacent to the fibres are adversely affected.

In the kraft process, most of lignin which has an adverse effect on the colour and strength of the cellulose fibre is removed and the final product is mostly de-lignified. The specific gravity of cellulose fibres which is produced by the kraft method is about 1.5 (Smook 2002).

In the kraft process, most of the hemi-cellulose and lignin from cell wall are dissolved and the fibre collapses into a ribbon-shape structure (Smook 2002).

In the mechanical process, more lignin remains in the fibre. Therefore, cylindrical structure of fibre remains and the lumen (core cavity of fibres) also remains open. Therefore it is expected that compact structure of the ribbon shape of kraft fibre may be the reason for its better performance.

If the kraft process is followed by bleaching with a sequence of oxidizing agents, the left lignin (about 10%) is removed. Bleaching leads to an increase in modulus of elasticity, flexural strength and reduced the toughness (Bentur 2007). This was associated with a different mode of failure so that the bleached fibre composite exhibits a more unstable and brittle performance with a sharper load drop after the maximum load was reached during a flexural test. It seems bleaching leads to an improved bond between the fibres and the matrix.

Figure 2-15 and 2-16 compared the flexural strength of fibre cement board reinforced by the kraft and TMP *P. radiate* fibre in both air-cured and autoclaved conditions (Bentur 2007).

Figure 2-15 Flexural strength versus fibre content for various FCB products (Bentur 2007)

As seen in figure 2-15 and 2-16, the flexural strength of the cement board reinforced by TMP fibres in extremely lower that the kraft fibres.

Figure 2-16 Effect of type of pulping process (kraft versus TMP) on the development of flexural strength in cement boards (Bentur 2007)

Two important issues in Fig. 2-16 are observed,

1) The kraft fibre could improve flexural performance rather than TMP fibre.

2) After 14 days casting, the rate of increasing flexural strength for all types of cement boards is very slow. In other words, in spite of neat cement which needs 28 days for curing, the fibre cement board normally needs only 14 days for curing.

During the past two decades much attention has been drawn to the use of cellulose fibres in cement boards due to their compatibility with cement matrix particularly their consistency with the Hatschek process. As a result of intensive research and development, cellulose-pulp fibres were used in some places as partial or full

replacement for asbestos in cement composites (Ashori et al. 2011, S.R 2010, Tonoli et al 2010 and Coutts 2005).

Coutts (1987) studied cement board reinforced by eucalyptus wood fibres prepared with a room temperature cured matrix. The comparisons between different types of pulping process that were carried out on eucalyptus indicate that the composites produced have different flexural strength. These differences cannot be explained on the basis of density (which is similar in all the specimens), or the strength of fibres. The better performance of the eucalyptus fibres processed by the kraft method was attributed to the higher fibre aspect ratio and less amount of lignin.

2.5.3.1 Refining or beating

Refining or beating can be defined as the mechanical action on cellulose fibres in the presence of water typically by passing the suspension of pulp fibres through a relatively narrow gap between a revolving rotor and a stationary stator both of which carry bars or knives aligned more or less across the line of flow of the stock (Coutts 2005). The term "beating' is usually applied to a batch treatment of pulp suspension, whereas 'refining' is used when the stock is passed continuously through one or more refiners in series.

It should be noted that the refining of chemical pulp does not produce the same effects as it does on mechanical pulps as chemical pulps are relatively pure cellulose with the hydroxyl groups easily accessible whereas in mechanical pulps the hydroxyl groups are blocked by the presence of lignin. The refining of mechanical pulp is really a completion of the process of disintegration of fibre bundles down to individual fibres.

Refining has an important effect in producing a large surface area for bonding in fibre - fibre or fibre – matrix interfacial zone, more importantly, can assist in controlling the

drainage rates of processing liquids during the fabrication of products (i.e. Hatschek process). This is one of wood fibre's main advantages compared to synthetic fibres such as glass, steel, etc., in asbestos replacement.

Considering all aforementioned in this section, it can be concluded that characteristics of cellulose fibres depend on the method of pulp processing, the type of refiner, the refining conditions used and the fibre type (hardwood or softwood).

2.6 Hybrid fibres as asbestos replacement

In this section, the results of the research carried out works on composites reinforced by hybrid fibres (usually cellulose-pulp fibre and synthetic fibre) are reviewed in viewpoint of physical, mechanical and durability properties.

The reason for applying hybrid fibres in manufacturing cement boards could be categorised into three following issues.

In some cases, the strength values obtained with cellulose fibres are not sufficiently high to be adopted for various applications, and they need to be stronger in flexural strength or fracture toughness.

Many types of cellulose fibres do not have ample resistance in alkaline media. So using synthetics fibres which are resistance in alkaline media could increase the durability of cement board.

In some cases, accessibility and providing large amount of high quality cellulose fibres does not have economical justification.

Almost, in all cases when cellulose fibres are used in combination with synthetic fibres the fibres serve different functions, processing and reinforcing. The cellulose functions

as a processing fibre with the synthetic fibres which are typically stronger and stiffer providing the reinforcing effect in the hardened matrix.

In cement board industry, cellulose fibres are used to assist in the manufacturing of fibre cement boards containing polyacrylonitrile, polyethylene, acrylic, carbon, glass, and polyvinyl alcohol fibres.

The characteristics of cement board reinforced by carbon fibres were studied by Xu et al (1999). They demonstrated that the strength of cement paste is increased by 56% and the modulus and ductility are increased by 39% by using silane-treated carbon fibres and silane-treated silica fume in comparison to the values for cement paste reinforced by untreated carbon fibres and silica fume.

They attributed this behaviour to the hydrophilic nature of silane which improves wettability of fibres and thus fibre-matrix bond would increase.

Ganjian et al (2008) that were seeking the replacement for asbestos fibre in cement-based products studied the flexural strength of cement board reinforced by blending of cellulose and acrylic fibres. They used 2, 4 and 6 % cellulose fibre (by the cement weight) in conjunction with 0.5, 1 and 2% acrylic fibres.

Their results indicated that the fibre contents and types affect the flexural performance and fracture toughness of composite sheets significantly. They also showed that there is an interaction between kraft and acrylic fibres in the cement composite sheet so that with increasing the amount of kraft fibre in constant acrylic amount, the flexural strength decreases. The optimum percentage of kraft fibres for use in cement sheets depends on not only the amount of kraft fibres but also the amount of acrylic fibres used. Based on their results, one percent acrylic fibres blended with two percent kraft

fibres give the optimum blended amount for the used fibres. Their results showed that the acrylic fibres are more effective with lower content than kraft fibres in the cement composite sheets.

Generally, most of the synthetic fibres as a result of hydrophobic characteristics have poor fibre-cement interfacial bonding. Therefore it is necessary to enhance interface bond properties. Many of the studies have focussed to resolve this imperfection.

An investigation was performed into the addition of reactivity materials such as calcium sulphoaluminate, metakaolin or silica fumes to reduce the concentration of hydroxyl ions in the pore solution. The results demonstrated that these materials could produce a less aggressive environment for the cellulose fibres (D.D 1995).

In most cases, used pozzolanic materials in cement matrix not only act as filler but also have positive effect in providing a cementitious binder that contributes to improve the matrix strength within the cement composites.

Marikunte et al (1997) reported that cement based composites containing 10% of silica fume could improve compressive strength, lower water absorption, lower coefficient of chloride ion diffusion, lower penetration of chloride ions and higher polarization resistance than those of control specimens. They also showed that the addition of silica fume could improve the permeability of fibre cement composites due to the positive effect from pozzolanic reactions which produces denser and more homogeneous structures and bonding within the matrix.

Many fibre cement composite products that are used in construction are required for use outside or in aggressive environments such as roofing and cladding. Investigations into the use of silica fume in non-asbestos fibre cement composites have shown that it

can enhance bending strength and density while it reduces porosity and water absorption. These qualities could make fibre cement composites containing silica fume significantly more resistant to freeze-thaw effects. The use of pozzolanic materials as a partial weight replacement for cement has also been investigated in order to reduce the alkalinity of the cement matrix as well as refining the pore structure of the matrix. Silica fume used at relatively large amounts (i.e., 30% or greater replacement of cement by weight) appears to significantly minimize composite degradation due to wet/ dry cycles (Schreiner et al. 2002).

Wu et al (1999) reported that the polyethylene fibres –cement interfacial bonding could be improved by plasma treatment. Plasma is produced by exiting gas molecules with a source of electrical energy. According to their results, using plasma treatment on these fibres could increase bond strength and interfacial toughness six times. They also suggested that this treatment could create a distinct interfacial chemical bond which is much greater than a common frictional bond. The mechanism of this treatment is the removal of hydrogen atoms from the synthetic backbone followed by their replacement with polar groups. The presence of polar groups could enhance reactivity with cement. This results in an appropriate adhesion and bonding within cement- fibres.

Glass fibre was on the attractive fibres for researchers for reinforcing fibre cement boards. But the main concern of this fibre is its durability in alkaline media of cement.

To overcome this problem, Alkaline Resistance glass fibre (AR-glass) was used in conjunction with pozzolanic materials. But a research (Marikunte et al. 1997) showed that deterioration of fibres still exist even the cement board reinforced by AR-glass. In that research an experimental investigation on the hot-water durability of glass fibre reinforced cement composites was conducted for their flexural and tensile performance.

Three different cementitious materials were selected: (a) cement; (b) cement + 25% metakaolin; and (c) cement + 25% silica fume. After curing for 28 days, specimens were immersed in a hot water bath at 50°C for 84 days and then tested for flexure and tension. The results showed that the blended cement with metakaolin improves the durability of cement boards reinforced by AR-glass significantly.

Mohr et al (2005) and Ahmed et al (2007) reviewed various durability characteristics of fibre cement boards. They showed that cement composite with tight crack width significantly resists the migration of aggressive substances in to the matrix. And the most important factors on tight crack width are related to uniform distribution of fibres, low permeability which gained by using appropriate filler and low water cement ratio.

Hansen et al (2009) investigated the effect of wind, snow or traffic on cement composite which is used for roofing. Also, the effect of the internal loads as a result of differences in temperature and moisture strains was studied in that research. The purpose of that investigation was to analyse the safety of the fibre cement boards in transmitting the designed loads during the lifetime of the composite The base of their research established on a theoretical and an experimental investigation of the strength and stiffness characteristics of unexposed cement sheets and those cement sheets that had been exposed on a roof in three years. They showed that as a result of the wave form of the profiled sheets, there are strong direction along the profiles and a weak direction across the profiles. In the strong direction, the critical property is the capacity to transmit concentrated loads and thereby the ability to transmit the dynamic effects from persons moving on the roof. The easiest method to increase this capacity is to change the geometry of the sheets. With increasing the thickness by 10%, the capacity

to transmit concentrated loads increase by 9%. But if the wave height increases by 10%, the capacity to transmit concentrated loads increase by 17%.

In the weak direction it should be avoided, fastening the screws too tight gives rise to pre-stress. There are two good reasons to avoid pre-stressing the screws;

- Risk of cracking reduced
- If the sheets are under stress during service loads, they will be vulnerable against environmental conditions.

Durability of roofing tiles manufactured by several formulations of cement composite reinforced with sisal and eucalyptus fibres was investigated in tropical climate by Roma and co-workers (2008). They indicated that a severe reduction in the mechanical properties was observed. After four months of ageing under external weathering the toughness of the vegetable fibre–cement fell to 53–68% of the initial toughness at 28 days of age. This behaviour was attributed to alkaline attack and deterioration of the natural fibre containing large amount of lignin. They found out that a high porosity of cement composite is associated with water absorption of at least 30% by mass which lead to an increase in vulnerability of cement board under external weathering.

Chapter 3: Materials and their characteristics

3.1 Natural waste fibres and synthetic fibres

3.1.1 Natural fibres

The fibres were prepared from different sources of agricultural waste. Four types of fibre were used: bagasse fibres (**BF**), wheat fibres (**WF**), eucalyptus fibres (**EF**) and kraft Pulp fibres (**K**).

Bagasse fibres are the solid cellulosic fibres left after the extraction of juice from the sugar cane stalk. In the same way, *wheat and eucalyptus* fibres are obtained from the stalk of wheat and eucalyptus respectively. *kraft pulp* fibres are obtained from waste cardboard. Except for kraft pulp fibres, the other natural fibres were bought from the market or collected from waste materials of agricultural companies. Fine particles of fibres of less than 150 microns and long fibres of more than 3 millimetres were separated so the lengths of used fibres were between 150 microns and 3 millimetres.

The kraft pulp (K) fibres were made in the laboratory. The procedure of preparation of the kraft pulp fibres is described as follows:

Cardboard was shredded into small pieces (≈ 10*10 mm). Then their weight was measured. Potable water (water/cardboard ratio 4:1 by the weight of cardboard) was added to keep the shredded pieces just submerged (figure 3-1). After three days the cardboard pieces were ready for further processing. The water was squeezed out manually and the pieces were blended in a mixer.

After about two hours of blending, the cardboard pieces were changed into pulp. Then the water content of the pulp was determined by measuring the weights of wet and oven dried pulp.

Figure 3-1 Shredded cardboard pieces were submerged in water

Measurements of the fibre dimensions for all types of fibre were conducted according to the Technical Association of the Pulp and Paper Industry (TAPPI) Test Method T 271 using an automated optical analyzer (table 3-1).

3.1.2 Synthetic fibres

As already mentioned, one of the most important synthetic fibres used as a replacement for asbestos fibres in cement board production is PVA (poly vinyl alcohol). These fibres are expensive (≈ 2,000 GBP per ton) and only a few countries have the technology to produce these fibres. According to the objectives of this research, an effort has been made to find accessible and cheap fibres as an alternative to asbestos. Therefore, based on the previous studies and

primary conducted tests, two types of synthetic fibre, which are produced in most countries and are much cheaper than PVA (approximately 30% cheaper) were selected including acrylic and polypropylene fibres.

3.1.2.1 Acrylic fibres (AC), which are called polyacrylonitrile (PAN), are synthetic fibres prepared by the polymerization of acrylonitrile. Acrylonitrile (C3H3N) is obtained by reacting propylene (C3H6) with ammonia (NH3) and oxygen in the presence of catalysts.

These soft and flexible fibres (PAN) have no hazardous properties, are hard to dissolve, and are resistant to most solvents and chemicals. Most properties of these fibres are close to wool; for this reason, the most common use of acrylic fibres is in apparel and carpets as a wool replacement.

Characteristics of used acrylic fibres are in table 3-2.

3.1.2.2 Polypropylene (PP) is a thermoplastic polymer. It has a linear structure based on the monomer CnH2n. This polymer is manufactured from propylene gas in the presence of a catalyst such as titanium chloride. PP is a by-product of oil refining processes.

These fibres are used in a wide variety of applications, including textiles, ropes, packaging, carpets and plastic parts, and even as reinforcement fibres in concrete.

3.1.3 Characteristics of natural fibres

3.1.3.1 Freeness

One of the main characteristics of the natural fibres within the cement matrix is freeness. This test has been designed to measure the drainage properties of natural fibre pulp. As a matter of

fact, the freeness of pulp is tested to give a measure of the rate at which a dilute suspension of pulp may be drained.

The result of this test depends on many variables, such as the number of fine particles, the morphology of fibres, types of fibre, fibrillation degree, flexibility of fibres, and the finesse modulus (Dinwoodie 1965).

The freeness of pulp is designed to give a measure of the rate at which a dilute suspension of pulp (3 g of pulp in 1 L of water) may be drained. The freeness, or the drainage time, of pulp is related to the surface conditions and swelling of the fibres. Drainage of unrefined pulp, which is measured as freeness, can give an indication of:

- The fibre length of pulp, as long fibre pulps have more freeness compared to short fibre pulps.
- Damage to fibres during pulping, bleaching or drying, so that short fibres or fines that produced during the pulping operation reduce pulp freeness.
- The refining energy required to achieve certain slowness during stock preparation.

In this study, the freeness test was carried out according to the AS/NZS 1301.206s:2002 standard. Freeness is commonly called Canadian Standard Freeness (CSF) because it has been based on the test developed by the Canadian Pulp and Paper Research Institute. For the current study CSF=450-550 was gained for all types of fibre used.

3.1.3.2 Mechanical and physical properties

Some of the most important physical and mechanical properties of the fibres were tested and are summarized in table 3-1.

Table 3-1 Test results of natural fibres' characteristics

Fibre type	Bagasse	Eucalyptus	Wheat	***kraft
*Average length (mm)	1.303	1.12	1.238	.87
*Average diameter (mm)	0.348	0.480	0.345	-
**Average tensile strength (MPa)	30	19	6	-
Aspect ratio	3.744	2.3	3.588	-
Freeness	520	450	480	550
Specific gravity	1.15	1.12	1.1	1.5

* Average length and diameter obtained from 50 fibres of each type.

** Average tensile strength obtained from 10 fibres of each type (measured standard deviation for tensile strength of bagasse, eucalyptus and wheat fibres were 2, 3.5 and 5 MPa respectively).

*** Pulp fibres have ribbon shapes (not cylindrical shapes) with 20-35 micron width. Also, measuring the tensile test was impossible due to the short length of the fibres.

The specific gravity of these natural fibres was a little bit more than one because when they were put in the water they went down very slowly. The specific gravities of 1.1, 1.15, 1.12 and 1.5 for wheat, eucalyptus, bagasse and kraft pulp respectively were measured by helium pycnometer.

3.1.4 Characteristics of synthetic fibres

The characteristics of the used synthetic fibres are given in table 3-2. As seen, one type of acrylic (length 5 mm) and two types of polypropylene (length 3 and 6 mm) were used.

Table 3-2 Test results of synthetic fibres' characteristics

Fibre type	Polypropylene	Acrylic
Average length (mm)	3 ±0.5 6 ±0.5	5 ±0.5
Average diameter (micron)	18-22	18-22
Average tensile strength (MPa)	250-300	350-400
Aspect ratio	150 300	250
Specific gravity	0.91	1.18
Elongation at break (%)	15-18	2.5-4

3.1.5 Alkaline resistance

Generally, degradation of natural fibres encased in Portland cement is due to the high alkaline environment which dissolves the lignin and hemicellulose phases, thus weakening the fibre structure. Therefore, less lignin in natural fibres leads to less degradation.

Measuring the alkaline resistance of the above mentioned natural fibres was very difficult because the fibres' lengths were short and submerging the fibres in alkaline solutions caused

weakness in them so doing tensile strength tests was hard. Therefore, it was obvious that all types of the above natural fibres faced a weakness in alkaline media but it was impossible to find out how much they decreased in strength or other characteristics.

As wheat, eucalyptus and bagasse fibres are obtained from agricultural waste products, the procedure for manufacturing these fibres is similar to mechanical pulping and a great amount of lignin (≈ 60%) remains in these fibres (as mentioned in 2.5.3.1). kraft pulp fibres, which are obtained from waste cardboard, have less lignin because in manufacturing cardboard chemical methods are used.

Both types of synthetic fibre were resistant in alkaline media and their tensile strength reduced less than 10% and less than 5% for acrylic and polypropylene fibres respectively. They were put in a saturated aggressive solution of calcium hydroxide (pH=14) for two weeks and then were subjected to a tensile strength test (table 3-3).

Table 3-3 Alkaline resistance of used synthetic fibres; Average tensile strength (MPa)

Fibre type	**Polypropylene**	**Acrylic**
Before saturation in alkaline media	250-300	350-400
After saturation in alkaline media	230-270	330-360

3.2 Other materials

In addition to the natural and synthetic fibres, cement (C), water and additives were used in the mixes.

Cement (C): ordinary Portland cement Type I, obtained from a Tehran cement factory, based on Iran national standard number 389 which is very similar to BS EN 197-1.

The properties of cement used were

- Cement type I-525 based on BS EN
- Blain surface area 2850 cm^2/gr
- 2-day compressive strength 2.2 MPa
- 28-day compressive strength 5.4 MPa
- MgO 4%
- SO_3 2.5%

Water: potable water was used for preparation of the specimens.

In some specimens, the effects of two additives, limestone powder (L) and Micro silica fume (M), were investigated. These materials were used as replacements for cement in some selected mixes.

3.2.1 Limestone powder

In table 3-4 some of the most important chemical analyses of the used limestone powder (Ca CO_3) are determined.

Particle size analysis for used limestone powder is depicted in figure 3-2. As can be observed, the size of most particles is less than 50 micron.

Table 3-4 Chemical analyses of limestone powder

Constitutes	Composition
$CaCO_3$	96.10%
$MgCo_3$	1.53%
Al_20_3	0.70%
Fe_2O_3	0.38%
Other	1.29%

This test was done by a Malvern Mastersizer 2000 machine. According to the instructions for this machine, the used technique is based around the principle that particles passing through a laser beam will scatter light at an angle that is directly related to their size. As the particle size decreases, the observed scattering angle increases logarithmically. The observed scattering intensity is also dependent on particle sizes and diminishes, to a good approximation, in relation to the particle's cross-sectional area. Large particles therefore scatter light at narrow angles with high intensity, whereas small particles scatter at wider angles but with low intensity.

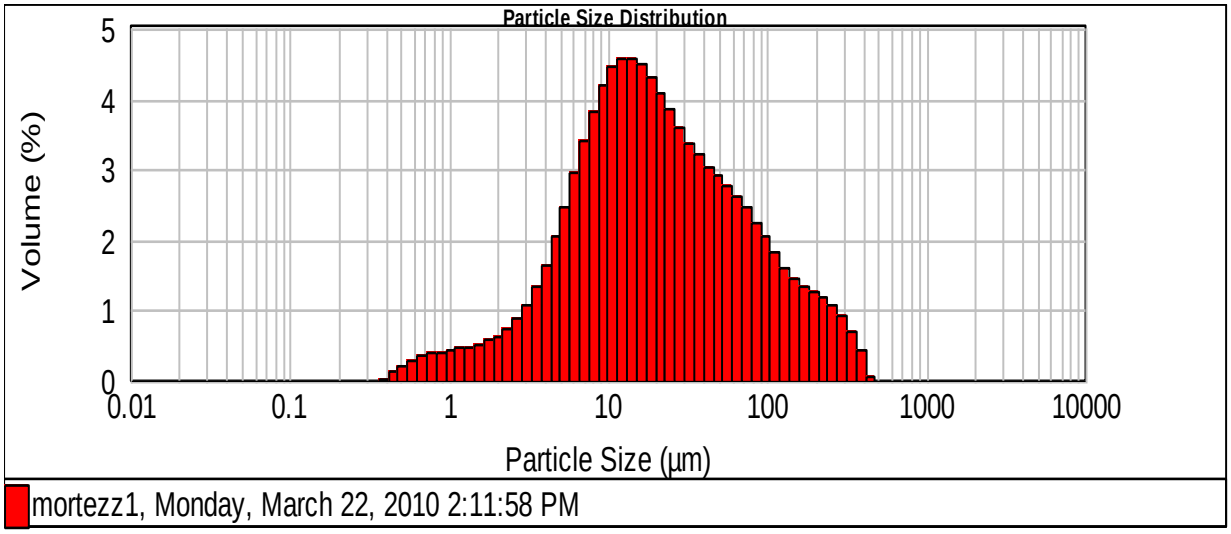

Figure 3-2 Particle size distribution of limestone powder

3.2.2 Silica fume

Silica fume is very fine noncrystalline silica produced by electric arc furnaces as a by-product of the production of metallic silicon or ferrosilicon alloys.

In some specimens, amorphous-micron powder of silica-fume (obtained from Iranian Azhand concrete factory) was replaced for cement weight. Specifications of the used silica fume are presented in table 3-5.

Table 3-5 properties of used silica fume

Colour	Grey
Specific gravity	2.35
Solubility	Insoluble
Silicon dioxide (SiO_2) %	94 %
Moisture content %	1.5 %
Oversize percent retained on 45-µm (325 sieve)	1.5 %
7-day pozzolanic strength activity index	107 %
Specific surface	18 m^2/g

The result of the particle size analysis test for silica fume is depicted in figure 3-3

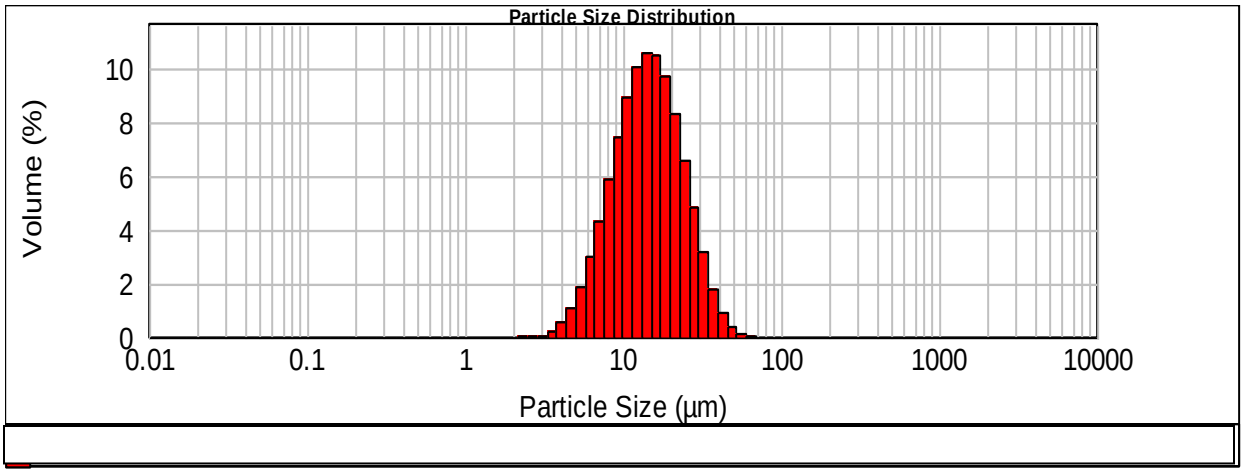

Figure 3-3 the result of particle size analysis test for silica fume

As can be seen, most parts of silica fume are smaller than cement particles (75 micron) and approximately continuous grading can be observed in particle size analysis.

3.3 Materials used in the factory trials

As will be explained in the next chapters (i.e. section 4.3.4 and 6.3), the kraft pulp fibres and acrylic fibres were chosen to make trial specimens in the factory. The kraft pulp was made out of waste cardboard. The method of preparation of these fibres will be described in chapter 6. The acrylic fibres were purchased from Esfehan acrylic factory in Iran (the acrylic used in the laboratory was provided by this factory too). Silicon based antifoams were used in very small amounts in the factory. The cement was purchased from the North cement factory in Iran.

Chapter 4; Specimen production and testing

In order to identify the details of Hatschek process, two asbestos cement board factories were visited and all stages in the production lines were analysed. Figure 4-1 shows a very basic schematic plan of the Hatschek process (already schematic shape of the Hatschek machine with more detail was illustrated in figure 2-9) . As can be seen, dilute slurry is in contact with the conveyor belt in bin containers while sieve cylinders are rotating, then a vacuum pump sucks excess water.

Figure 4-1 Schematic plan of Hatschek process (Kuder, 2003)

4.1 Developing a slurry vacuum dewatering system

To establish the governing principles of the Hatschek process to set up a system to make the specimens in the laboratory, it was essential to recognize all the details of the Hatschek process to produce a cement sheet. Based on visits to the factories, two important stages of the Hatschek process were determined (Figures 4-2 and 4-3). The minimum required capacity of the Hatschek machine to produce asbestos cement sheet is around 450 Kg cement and 60 Kg asbestos fibres.

Figure 4-2 Photograph of sieve cylinder in contact with conveyor belt

As can be seen, the outline of the conveyor belt includes a cement sheet with an approximately one millimetre thickness twisted on the accumulator roll. After around 5-6 windings, the required thickness of the cement board (normally around six millimetres) is obtained.

Figure 4-3 Photograph of the function of the accumulator roll in making a cement sheet with the desired thickness

4.1.1 Design of mould for lab dewatering system

Based on research carried out by the author, there has not yet been invented a laboratory Hatschek machine to produce cement board with capacity of less than 10 Kg cement. So it seemed providing a Hatschek machine to laboratory scale is nearly impossible. However, an attempt was made to establish the Hatschek process principles in the laboratory. To this end, a particular mould was designed with the following specifications. In figure 4-4 some of the parts of the mould are shown.

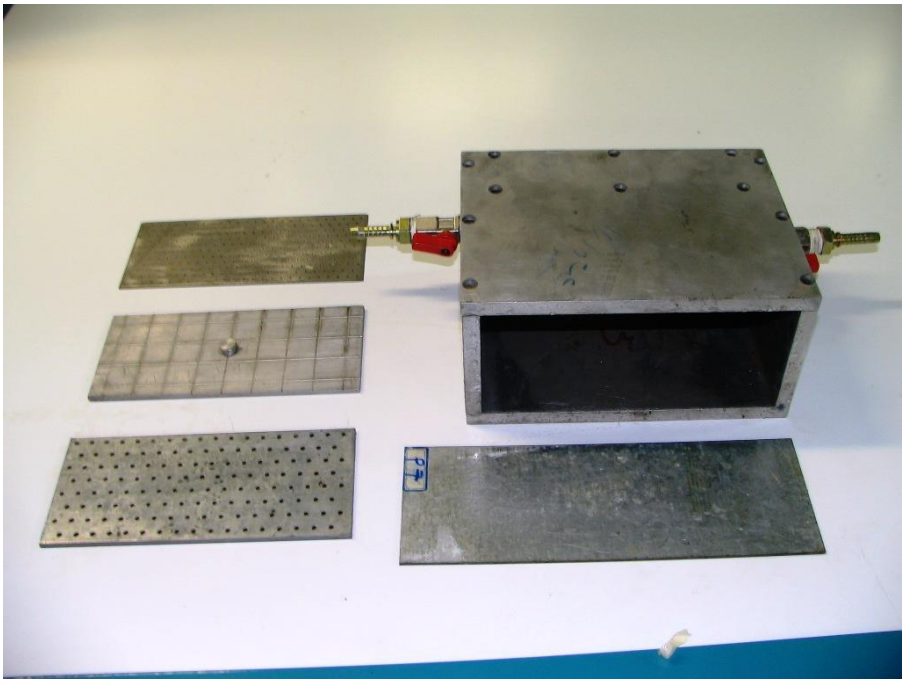

Figure 4-4 All the important parts of the laboratory mould

As can be observed, there are two perforated plates, which are used for drainage of the excess water from the slurry. The fibres must be mixed with a high water content otherwise uniform distribution of fibres is not achieved. That is why a vacuum pump is applied to remove the excess water.

In figure 4-5 a rectangular prism, which is used to pour the slurry, is depicted. Two perforated plates are placed in the mould and, when slurry is poured in the mould, the excess water is sucked by the vacuum pump.

In figure 4-6 a vacuum pump and a conical flask are depicted. The vacuum pump is connected to the conical flask and that is connected to the mould to suck excess water. The specification of

the vacuum pump was: nominal capacity: 7.6 m^3/h, final vacuum: <0,005 mbar, motor power: 1/2 HP.

Figure 4-5 Rectangular prismatic aluminium mould for making the specimens in the laboratory

Figure 4-6 Laboratory equipments for making the specimens

4.1.2 Trial test in the laboratory

After preparing the mould and other equipment, many trial specimens were made to find a suitable proportion of ingredients for making laboratory specimens. Some of the most important parameters were: making a specimen around 6 millimetres in thickness, making slurry of cement and other ingredients with suitable water/cement ratio, finding suitable power for the vacuum pump to suck excess water and finding an appropriate method to blend all the ingredients, particularly resulting in a uniform distribution of fibres in the mix.

To this end, more than 50 mixes were made and following results were gained.

The thickness of specimens depends on the amount of fibres and other ingredients. To make a specimen (6 millimetres in thickness) without any fibres, approximately 200 grams of cement is required. With increasing the fibres the amount of cement should be decreased. Also, experience

of making more than 50 specimens showed that the proper water/cement ratio for making slurry is 3.5.

4.2 Specimen production

In this section, details of how to make a specimen in the laboratory are explained. These include: preparing the fibres, mixing the ingredients, casting and curing processes.

4.2.1 Specimen mixing process

Before mixing the ingredients, fibres need to be processed. The most important processing of natural fibres in order to use them in fibre cement board is called ‘beating or refining’. Generally, ‘refining’ is a mechanical process that increases the lateral surface of natural fibres. The structure of natural fibres is approximately similar to a piece of rope. Rope is a helical wrap of strands which themselves are helical wraps of fibers. If one twists a rope in the direction of the helical wrap the rope becomes stiffer; likewise, if the twist is in the opposite direction the rope unwinds (or delaminates) to open up the structure and becomes ‘fluffy’. This process leads to increased fibre flexibility and swelling. Therefore, all factories which apply cellulose fibres to produce cement board should have a refiner to process the cellulose fibres. In a refiner, damped fibres are fibrillated by passing the suspension of pulp fibres through a relatively narrow gap between a revolving rotor and a stationary stator. Figure 4-7 shows a refiner in non-asbestos fibre cement board.

There are some points that should be noted about the refining process. Depending on the forces acting on the fibres during refining, some fibrils are separated from the surface of the fibres. These substances would have unfavourable effects. Fibre shortening is another side effect

attributed to refining. This may occur as a result of the cutting action of the blades or discs in the machinery on the single fibres.

a) General view of the refiner used in factory

b) Display revolving rotor and a stationary stator

Figure 4-7 Ordinary refiner in non-asbestos fibre cement board (Courtesy of Eternit factory, Belgium)

In the laboratory, the amount of required fibres to make a specimen is less than 100 grams so using the refiner set, which works with a minimum of 10 Kg of fibres, is impossible. Therefore, with consultation of an expert wood industrial engineer, a pestle and mortar were used to refine the small amount of natural fibres in the laboratory (Fig 4-8). It should be noted that beating fibres in the mortar must be accompanied with a twisting motion of the pestle through pressure on the mortar. This twisting motion allowed the micro fibrils to unwind from the core stem to allow for suitable fibre fibrillation. This process increases the fibres' lateral surface areas and creates micro fibrils, which could enhance the bonding strength between the fibres and matrix.

Mechanical treatment (i.e. beating fibres for five minutes) was the only treatment done on the natural fibres and no treatment was conducted for the synthetic fibres. To improve the fibre

characteristics in the mixes, they were submerged in water for 48 hours, and then the fibres were subjected to above mentioned process.

Figure 4-8 Beating fibres in order to refine the natural fibres with pestle and mortar

The natural fibres were then poured into a beaker where half the required amount of water (200 gr) in the mix was added. The cellulose fibre solution was then mixed using an overhead propelling mixer (Fig 4-9) with a narrow blade (30 * 10* 1 mm) for three minutes; this ensured that the fibres did not clump together and that the fibres were uniformly distributed in the water. A propelling rate of 1700-2000 rpm was used.

Figure 4-9 Overhead propelling mixer to unravel the natural fibres

4.2.2 Specimen casting and curing process

In order to create uniform dispersion of fibres and approximate simulation of the Hatschek process in the laboratory, manufacturing of the specimens were carried out as follows.

After beating and unravelling with overhead propelling mixer the cellulose fibres and cement were placed in a mixer with 200 grams of water to further disperse for 5 minutes (Fig. 4-10).

Figure 4-10 Mixing all ingredients in a Hobart mixer with whisk blade

All ingredients, i.e. silica fume, limestone powder, water, cement and synthetic fibres were measured using an accurate digital scale of 0.1 gr and placed into a conventional mixing bowl and mixed using a whisk blade. Before pouring the slurry into the mould, it was lubricated by mould oil then two perforated plates with different diameter holes were placed inside the mould. The plate with big hole was placed at the bottom of the mould, then the plate with smaller holes was placed on top of it. At the end, a filter paper cut to fit the mould size was placed on top of the perforated plates.

Then, after careful mixing, three successive layers of the slurry poured into the mould, comprising perforated stainless steel plates with filter paper on the last layer, and the vacuum pump was switched on to drain the excess water from the slurry. The perforated plate with filter paper on it retained cementitious particles with fibres while the excess water was drained off through suction by the vacuum pump. The vacuum pump, conical flask and aluminium mould made a circuit to suck excess water from the mix.

It took about 5 minutes and then was switched off. At this stage, after forming cement board with consecutive layers of slurry to achieve the required thickness, a weight of 10kg was uniformly applied to level of the paste inside the mould, then the pump was switched on again for about 5 minutes to drain the remaining excess water to form a fibre cement sheet paste that is not too wet.

By subtracting the primary water and sucked water, the water/cement ratio could be calculated. For most of the specimens, the water cement ratio was about 0.34 up to 0.36.

Then the specimen was demoulded and labelled according to the design code, curing time required, date and sample number.

The dewatered specimens were allowed to dry for approximately 1 hour before being stored in a chamber at 95 ± 5 % relative humidity and 20 ± 2 °C for either 7 or 28 days before relative mechanical, physical or durability testing.

Figure 4-11 shows some produced specimens. The dimensions of each specimen (flat cement sheet) length, width and thickness were 182mm, 82mm and 7mm respectively.

Figure 4-11 Some produced specimens in the laboratory

4.3 Mix design

Based on the goals of this research, there are some important criteria for choosing fibres and other ingredients for replacing asbestos fibres in cement sheet, such as accessibility and economy. Based on these aims, some of most accessible and cheap fibres and materials as described in chapter 3 were selected.

After preparation of the system and doing the trial tests, many specimens were produced in three stages include primary, secondary and final mix designs. These stages are presented in this section

4.3.1 Principal concept

According to previous research described in the literature review chapter, there are many parameters influencing the mechanical, physical and durability characteristics of cement boards.

Some of the most important parameters which have been considered in this research are as follows:

1- types of fibre
2- amount of fibre content
3- natural fibre–synthetic fibre interaction
4- effect of additives to improve cement board properties

Based on the above mentioned parameters, three mix groups were designed.

In the primary or the first group, the types and amounts of the 'natural fibres' as base fibres to produce FCB (Fibre Cement Board) were investigated. As the flexural strength test is the most important mechanical test for FCB, only this test was done for the first group. The outcome of this stage led to a recognition of the fibres' behaviour in the cement matrix. Also, the kraft pulp fibres were selected as the best fibres within the four selected types of waste fibres and more research was conducted with this type of fibre in the secondary group.

Although natural fibres have many advantages, such as good compatibility with the cement matrix and being accessible and cheap, they also have some imperfections and limitations, such as shorting in length, weakness in high alkaline media, low tensile strength, swelling and shrinkage against changes in moisture.

It should be noted that synthetic fibres also have some limitations, such as weak bonding with the cement matrix, lack of fibrils and low density. As a result of these properties, synthetic fibres are not solely used in FCB (Coutts et al. 2005).

As can be deduced and has already been discussed in the literature review, to improve FCB properties (Coutts et al. 2005 and Ganjian et al. 2008), a blend of synthetic and natural fibres is suggested.

Therefore, in the second group, the interaction between natural and synthetic fibres was studied. As already mentioned in 3.1, two types of synthetic fibre, polypropylene and acrylic fibres, were selected and different proportions of these fibres in combination with kraft pulp fibres were investigated. The outcome of this stage showed that acrylic fibres can create better mechanical properties for FCB.

Based on the achieved result of the second stage, the third group of mixes was designed to investigate the effect of additives on the mechanical, physical and durability properties of FCB.

Finally, some of the best laboratory mix designs were selected and a few factory trials were successfully manufactured in an asbestos cement board factory.

4.3.2 Primary mix design

Table 4-1 shows the proportions of ingredients of the composites mix as a primary mix design plan for making the laboratory specimens. As has already been described, B, W, E and K have been used in this table to represent as **B**agasse, **W**heat, **E**ucalyptus and **kraft** pulp fibres.

The number after B, W, E and K in the mix code is the percentage of fibres by the cement weight, which was used in the mixes. For example, K2 means 2% kraft pulp fibres by the cement weight in the mixes.

Although it is possible to give the proportion of each ingredient by volumetric percent, it is common to give the amount of each ingredient by weight percent in cement board industries. As

observed in table 4-1, with increasing fibre content, the amount of cement decreases. Because this is based on observations in the laboratory, with increasing fibre content, the thickness of the specimens increases to more than 7 mm, which is not desirable.

Therefore to keep the specimens' thicknesses constant (5-7 mm), the amount of cement reduces. The reduction in the amount of cement for each group was obtained based on laboratory experiences.

Careful attention to table 4-1 shows that the amount of fibres for specimens reinforced by bagasse, wheat and eucalyptus have been limited to a maximum of 4%, while those specimens reinforced by the kraft pulp fibres were made with a higher percentage of natural fibres. Because when the percentage of these fibres (i.e. wheat, eucalyptus and bagasse) was greater than 4% by weight with respect to the cement, it disordered the specimens and fibres floating on the top of the mixture, clamping together and balling incidents were observed during the mixing procedure. In addition, when the fibre content was more than 4%, these fibres were not dispersed uniformly in the cement matrix. For this reason, only 2 and 4% by the weight of cement were applied to make the specimens. The kraft pulp fibres didn't create any problem and could uniformly disperse even in high percentages up to 14%.

Table 4-1 Primary mix proportion for specimens reinforced by natural fibres

Mix	Mix code	Cement (gr)	Wheat fibres (gr)	Bagasse fibres (gr)	Eucalyptus fibres (gr)	kraft pulp fibres (gr)
1	Control	200	0	0	0	0
2	B2	190	0	3.8	0	0
3	B4	180	0	7.2	0	0
4	W2	190	3.8	0	0	0
5	W4	180	7.2	0	0	0
6	E2	190	0	0	3.8	0
7	E4	180	0	0	7.2	0
8	K2	190	0	0	0	3.8
9	K3	185	0	0	0	5.55
10	K4	180	0	0	0	7.2
11	K5	175	0	0	0	8.75
12	K6	170	0	0	0	10.2
13	K7	165	0	0	0	11.55
14	K8	160	0	0	0	12.8
15	K9	155	0	0	0	13.95
16	K10	150	0	0	0	15
17	K11	145	0	0	0	15.95
18	K12	140	0	0	0	16.8
19	K13	135	0	0	0	17.55
20	K14	130	0	0	0	18.2

4.3.3 Secondary mix design

After analysing the results of the flexural test for primary mix designs, the results showed that the kraft pulp fibres, which are gained from waste cardboard, had suitable potential to produce fibre cement board (this will be explained in section 5.2.1.2). It means more attention should be paid to develop FCB reinforced by this type of fibre. Therefore table 4-2 was designed based on the outcome of analysing table 4-1.

As the best flexural strength was related to K8, so K8 was selected as a base parameter and many of the mixes were designed using K8 and synthetic fibres (polypropylene and acrylic). Analysis of the results of specimens with K8 as base fibres and different amounts of polypropylene and acrylic fibres showed that the flexural strength of specimens decreased; however, acrylic fibres demonstrated a better behaviour. At this stage, further research with polypropylene was ceased and the rest of research was concentrated to identify the interaction between different amounts of kraft fibres and different amounts of acrylic fibres.

Table 4-2 Secondary mix proportion for specimens reinforced by hybrid fibres

Mix	Mix code	Cement (gr)	kraft pulp fibres (gr)	Polypropylene fibres – 3mm (gr)	Polypropylene fibres – 6mm (gr)	Acrylic fibres – 5mm (gr)
1	K8PP0.5-3mm	150	12	0.75	0	0
2	K8PP1-3mm	145	11.6	1.45	0	0
3	K8PP1.5-3mm	140	11.2	2.1	0	0
4	K8PP0.5-6mm	150	12	0	0.75	0

Table 4-2 continued

Mix	Mix code	Cement (gr)	kraft pulp fibres (gr)	Polypropylene fibres – 3mm (gr)	Polypropylene fibres – 6mm (gr)	Acrylic fibres – 5mm (gr)
5	K8PP1-6mm	145	11.6	0	1.45	0
6	K8PP1.5-6mm	140	11.2	0	2.1	0
7	K8AC0.5	150	12	0	0	0.75
8	K8AC1	145	11.6	0	0	1.45
9	K8AC2	135	10.8	0	0	2.7
10	K8AC3	125	10	0	0	3.75
11	K6AC0.5	165	9.9	0	0	0.825
12	K6AC1	160	9.6	0	0	1.6
13	K6AC2	150	9	0	0	3
14	K6AC3	140	8.4	0	0	4.2
15	K4AC0.5	175	7	0	0	0.875
16	K4AC1	165	6.6	0	0	1.65
17	K4AC2	155	6.2	0	0	3.1
18	K4AC3	145	5.8	0	0	4.35
19	K3AC0.5	180	5.4	0	0	0.9
20	K3AC1	170	5.1	0	0	1.7
21	K3AC2	160	4.8	0	0	3.2
22	K3AC3	150	4.5	0	0	4.5
23	K2AC0.5	185	3.7	0	0	0.925
24	K2AC1	175	3.5	0	0	1.75
25	K2AC2	165	3.3	0	0	3.3
26	K2AC3	155	3.1	0	0	4.65

4.3.4 Final mix design

Based on the analysis of the results of the first and secondary mix designs, the final mix designs were designed. The outcome of previous stages showed that K8 and K4-AC3 showed the highest flexural strength and they also had a good toughness (this will explain in section 5.2). Therefore, more research to enhance the flexural properties of FCB using additives, i.e. limestone powder (L) and micro silicate (M), was carried out. Table 4-3 was designed to identify the effects of additives on improving FCB characteristics.

Table 4-3 Final mix designs to investigate the role of additives on FCB properties

Mix	Mix code	Cement (gr)	kraft pulp fibres (gr)	Limestone (gr)	Silica fume (gr)	Acrylic fibres (gr)
1	K8	160	12.8	0	0	0
2	K8-L5	152	12.8	8	0	0
3	K8-L10	144	12.8	16	0	0
4	K8-L15	136	12.8	24	0	0
5	K8-L20	128	12.8	32	0	0
6	K8-M3	155.2	12.8	0	4.8	0
7	K8-M6	150.4	12.8	0	9.6	0
8	K8-M9	145.6	12.8	0	14.4	0
9	K8-M12	140.8	12.8	0	19.2	0

Table 4-3 continued

Mix	Mix code	Cement (gr)	kraft pulp fibres (gr)	Limestone (gr)	Silica fume (gr)	Acrylic fibres (gr)
10	K8-L10-M3	139.2	12.8	16	4.8	0
11	K8-L10-M6	134.4	12.8	16	9.6	0
12	K8-L10-M9	129.6	12.8	16	14.4	0
13	K4-AC3	145	5.8	0	0	4.35
14	K4-AC3-L5	137.75	5.8	7.25	0	4.35
15	K4-AC3-L10	130.5	5.8	14.5	0	4.35
16	K4-AC3-L15	123.25	5.8	21.75	0	4.35
17	K4-AC3-L20	116	5.8	29	0	4.35
18	K4-AC3-M3	140.65	5.8	0	4.35	4.35
19	K4-AC3-M6	136.3	5.8	0	8.7	4.35
20	K4-AC3-M9	131.95	5.8	0	13.05	4.35
21	K4-AC3-M12	127.6	5.8	0	17.4	4.35
22	K4-AC3-L10-M3	126.15	5.8	14.5	4.35	4.35
23	K4-AC3-L10-M6	121.8	5.8	14.5	8.7	4.35
24	K4-AC3-L10-M9	117.45	5.8	14.5	13.05	4.35
25	K4-AC3-L10-M12	113.1	5.8	14.5	17.4	4.35

It should be noted that in table 4-3 the additives silica fume and limestone powder replaced for the cement. For example ‘K4-AC3-L10-M12’ comprises 4% kraft fibres, 3% acrylic fibres, 10% limestone powder and 12% silica fume. All mix proportions are given by the weight of cementitious material (cement + silica fume + limestone powder).

After analysing the results of flexural strength for tables 4-1 to 4-3, some of the mixes that had appropriate flexural performance were selected, replicated and subjected to durability tests.

At the end of the research, two of the mixes were chosen and a few prototypes were successfully made as non-asbestos cement sheet in an asbestos cement sheet factory.

4.4 Specimen testing

More than 70 different mixes were designed, made and tested in this research, as earlier explained in 4.3. Ten replicate specimens were produced for each mix proportion and a total of more than 700 specimens were manufactured. Total specimens made were more than 1000 because some mixes were selected to reproduce the specimens for durability tests.

In this research, flexural tests were conducted 7 and 28 days after the casting; the rest of the tests including physical and durability tests were carried out 28 days after the casting.

All possible provisions, such as using the same equipment (e.g. digital scales and vernier callipers), were considered at all stages to reduce the likelihood of instrument errors affecting the results. Also, a thermometer and a humidity tester were used to ensure all the specimens were conditioned within the specified limits for each test.

4.4.1 Mechanical test

Cement boards are normally produced in flat or corrugated shapes. They need to have ample strength against loading. Almost all relevant standards regarding cement boards (such as ASTM c 1185, BS EN 494 and BS EN 12467) assert that the flexural test is the most important test to evaluate the mechanical properties of FCB.

4.4.1.1 Flexural behaviour

Flexural behaviour of the specimens under a three-point load system according to BS EN12467:2004 was carried out at 7 and 28 days. This test was conducted on a HKS machine applying the load driving at a speed of a constant deflection rate of 10 mm/min.

This standard suggests 5 classes for flexural strength (specimens aged 7-14 days), as shown in Table 4-4

Table 4-4 Minimum failure strength for various classes according to the BS EN12467:2004

Class	Minimum flexural strength (MPa)
1	4
2	7
3	10
4	16
5	22

According to BS EN 12467, the results of the flexural strength test (or MOR: modulus of rupture) should be interpreted by calculating flexural stress as follows:

$$\sigma = \frac{3PL}{2BH^2}$$ Equation 4-1

Where

σ is flexural stress/modulus of rupture (MPa)

P is the breaking load (N)

L is the span of the simple supports (mm)

B is the width of the specimen (mm)

H is the thickness of the specimen (mm)

To do a flexural test, one support should be fixed and another one should be a roller that is free to move. According to BS EN 12467:2004 clause 7.3.2.2.1, the supports should be rounded with a radius greater than 3mm but less than 25mm.

Also, the test machine (fig. 4-12) must be set to a constant rate of loading (fulfilling criteria 7.3.2.2.1 BS EN 12467:2004).

Figure 4-12 Flexural strength test for FCB according to BS EN 12467:2004

4.4.2 Physical tests

The physical tests are commonly used to determine the serviceability of products during life time particularly when they are exposed to ambient conditions, considering tolerance of elements for installing the board on the frames, designing expansion joints, calculate the weight of products to design the frames and so on.

Generally, the physical tests in this research are dealing with some environmental tests as follows:

- Density
- Moisture movement
- Water absorption
- Moisture content

These tests show some of the most important characteristics of fibre cement board under environmental conditions that could be useful for practical application. In British Standard, there are no methods of testing for some of the above mention tests that are applicable for laboratory scale specimens. Therefore, to identify those characteristics, ASTM standards were used.

4.4.2.1 Density

To determine the density of the specimens, the water displacement method was applied, as shown in figure 4-13. To this end, the weight of the specimen in the air was measured using a top pan balance and recorded. The specimen was then placed on a cradle beneath the top pan balance (but attached) and then submerged under water. The weight under water was then recorded.

Figure 4-13 System to determine the density of fibre cement board

The following expression was used in order to determine the density of the specimen:

Equation 4-2

4.4.2.2 Moisture movement

Moisture movement is the linear variation in the length of specimen, with change in moisture content. This test is used to determine the serviceability of products in areas with high humidity and exposure to moisture. moisture movement test was carried out according to ASTM C1185.

Each specimen was conditioned to practical equilibrium at a relative humidity of 30 ± 2 % and a temperature of 20 ± 2°C. Practical equilibrium is defined as the state of time change in weight where, for practical purposes, the specimen is neither gaining nor losing moisture content more than 0.1 wt. % in a 24-hour period

The length of each specimen was measured using a micrometer with the accuracy of 0.01 mm. Then the specimens were conditioned to practical equilibrium at a relative humidity of 95 ± 5 % and a temperature of 20 ± 2°C and the lengths of the specimens were measured again.

The linear change in moisture content is the percentage change in length based on the length at relative humidity change from 30 to 90, i.e.:

Equation 4-3

4.4.2.3 Water absorption

A water absorption test was done to determine the tendency of a product to absorb water and sometimes determine uniformity of the product. The increase in mass of the test specimen expressed as a percentage of its dry mass after immersion in water for a specified period of time was determined. The test was carried out according to ASTM C1185. Each specimen was dried to a constant weight in a ventilated oven at a temperature of 90 ± 2°C and cooled to room temperature in a desiccator before being weighed. Then the specimens were submerged for 48 ± 8 h in clean water at 23 ± 3°C. Each specimen was then removed from the water, wiped with a damp cloth, and weighed, i.e. the water absorption percentage is given by Eq. 4-4:

$$(W_s - W_d)/W_d \pm 100 \qquad \text{Equation 4-4}$$

Where

W_s is weight of saturated specimen in grams

W_d is weight of dry specimen in grams

4.4.2.4 Moisture content

The percentage of moisture content of the fibre cement board when conditioned at 50 ± 5 % RH and a temperature of 23 ± 2°C was determined according to ASTM C1185. After equilibrium conditioning, each specimen was weighed to an accuracy of 0.5% of its initial mass (W). Each specimen was then dried to constant mass in a circulated oven at a temperature of 90 ± 2°C and cooled to room temperature in a desiccator and the final mass when oven-dried (F) was recorded. Moisture content percent is given by:

$$M = 100 \times [W - F) / F \quad \text{Equation 4-5}$$

4.4.3 Mechanical durability tests

Many types of cement board (i.e. cement boards used for external wall or cladding) are exposed to natural conditions such as freeze-thaw and wet-dry cycles during a long time of use. So the durability of those cement boards should be checked by accelerated tests.

It has been reported that some composites based on natural fibres suffer a severe lowering in flexural strength and modulus of elasticity after exposure for one year to temperature or tropical environments (Savastano et al. 2009). If the material yields unsatisfactory results, further investigation into fibre surface treatments and applying additives may be required to enhance durability properties.

In this research, to identify the durability characteristics of laboratory cement board, a freeze-thaw cycle test was carried out for some selected mixes that had shown high flexural strength and were deemed suitable for further testing.

4.4.3.1 Freeze/thaw

Test procedure

This test was done according to BS EN 494, 2007. In order to do the test, 20 specimens were chosen and prepared, as for the bending moment test described in 4.4.1.1. The specimens were then divided randomly into two lots of 10.

The first lot of 10 specimens were subjected to the breaking load test described in 4.4.1.1, including the conditioning procedure.

At the same time the second lot of specimens were immersed in water at ambient temperature (> 5 °C) for 48 h. Then they were subjected to 100 of the following freeze-thaw cycles:

The specimens were put in a freezer which had to reach a temperature of (-20 ± 4) °C within 1 to 2 h and were kept at this temperature for a further 1 h, then they were heated (thawed) in the water bath, which had to reach a temperature of (20 ± 4) °C within 1 to 2 h and needed to be held at this temperature for a further 1 h.

During both the cooling and heating (freezing and thawing) cycles the specimens were positioned so that they were able to experience free circulation of the conducting medium (air in the freezer or water in the bath) around them.

Each freeze-thaw cycle had to take between 4 and 6 h but an interval of 72 h maximum may be taken between cycles during which the specimens should be stored in water at 20 °C.

Control of the freeze-thaw cycles can be automatic or manual. Continuous automatic cycling is preferable.

After the 100 cycles were completed, they were examined with the naked eye for cracks, delamination or other defects and any observations should be recorded.

Then the breaking load test was carried out similar to normal specimens.

Expression and interpretation of results

For each of the two lots, the mean breaking load or bending moment and the standard deviation were calculated.

Let X1 and s1 be the mean and the standard deviation of the results obtained on the first lot, and X2 and s2 be the mean and the standard deviation of the results obtained on the second lot tested after the freeze-thaw cycles.

The L1 and L2 should be calculated by the following relationships:

$$L1 = X1 + (0.58 * s1) \quad \text{Equation 4-6}$$

which is the upper estimation of the mean breaking load or bending moment at 95% confidence level of the reference lot (first lot), and

$$L2 = X2 - (0.58 * s2) \quad \text{Equation 4-7}$$

which is the lower estimation of the mean breaking load or bending moment after freeze-thaw cycles at 95% confidence level (second lot).

Then the ratio, RL is calculated, as follows:

$$RL = L2/L1 \qquad \text{Equation 4-8}$$

After 100 freeze-thaw cycles, the ratio RL as defined in Eq. 4-8 should not be less than 0.70.

Also, any visible alteration should not be of such a degree as to affect the performance in use.

It seems alterations such as cracks, spall and swelling can affect the performance of products in serviceability.

Chapter 5; Results, analysis and discussion

In this chapter, the results of the tests carried out on specimens are presented, analysed and discussed. As already mentioned, the flexural performance of the specimens is discussed as the most important mechanical property of fibre cement board at the first section of this chapter. As will be seen, the mixes were modified to gain the highest flexural strength then, after finding the best mixes, physical tests were carried out on control specimens and twenty five different mixes that had obtained the highest flexural strength. Finally, mechanical durability tests were conducted on only three selected mixes that had the best mechanical and physical properties. To clarify interaction within fibres and matrix, microstructural studies carried out by SEM (scanning electron microscope) for selected specimens.

5.1 Results tables

The results of the conducted tests are investigated and discussed in this chapter. The mean values obtained from the specimen tests are given with more details in section 5.2.

The graphs of these tables are plotted in this chapter and the tables are given in appendix A.

Appendix A includes following tables:

A-1: Flexural stress (7 & 28 days) of laboratory specimens reinforced by waste natural fibres (fibre content is up to 4%).

A-2: Flexural stress (7 & 28 days) of laboratory specimens reinforced by waste kraft pulp fibres (fibre content is up to 14%).

A-3: Flexural stress (7 & 28 days) of laboratory specimens reinforced by waste kraft pulp fibres and polypropylene fibres (3mm and 6mm).

A-4: Flexural stress (7 & 28 days) of laboratory specimens reinforced by waste kraft pulp fibres and acrylic fibres.

A-5: Effect of limestone powder on flexural stress (7 & 28 days) of laboratory specimens reinforced by waste kraft pulp fibres.

A-6: Effect of silica fume on flexural stress (7 & 28 days) of laboratory specimens reinforced by waste kraft pulp fibres and acrylic fibres.

5.2 Flexural behaviour

Flexural behaviour includes flexural stress, toughness and ductility that each specimen has experienced during loading. In each step of loading, flexural stress is calculated with E.q 1-4 and the mid span deflection is measured.

In this research, for each group (mix), 10 specimens were replicated; 5 specimens were tested after 7 days and the other 5 specimens were subjected to flexural tests after 28 days. In all cases, the results were within 3% of the average of their group with a standard deviation of less than 0.25 MPa.

5.2.1 Natural waste fibres

In this research, four different types of natural waste fibre were studied: bagasse (sugar cane), eucalyptus, wheat and kraft pulp fibres. The studied parameters for specimens are too many to illustrate all of them in one graph, hence, the comparison of the flexural behaviour and analysis

are conducted in separate graphs and at the end of this section a bar chart graph shows the flexural strength of all mixes.

5.2.1.1 Wheat, bagasse and eucalyptus fibres

The flexural behaviour of specimens reinforced by wheat, bagasse and eucalyptus is shown in figures 5-1, 5-2 and 5-3. In these figures, one out of five specimens of each group (mix) with 7 days age and one of five specimens with 28 days age were chosen as representatives of the group to show its flexural behaviour. As the average flexural strength for each group is obtained by the average maximum flexural stress of all specimens in a group, the selected graph as a representative of flexural behaviour of each group is the graph that has the maximum flexural stress close to the average of the group.

Generally, the overall performances of specimens in each group are similar to each other; however, there are small differences within the flexural behaviour of each specimen in a group.

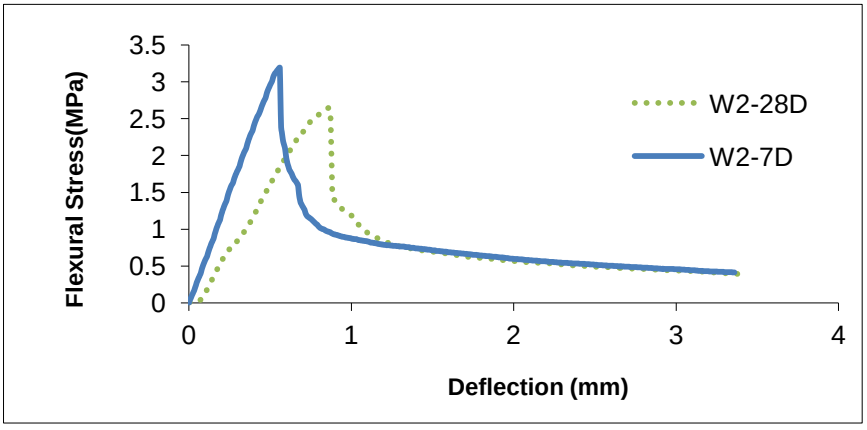

Figure 5-1 Flexural behaviour of FCB reinforced by 2% wheat fibres (7 & 28 days)

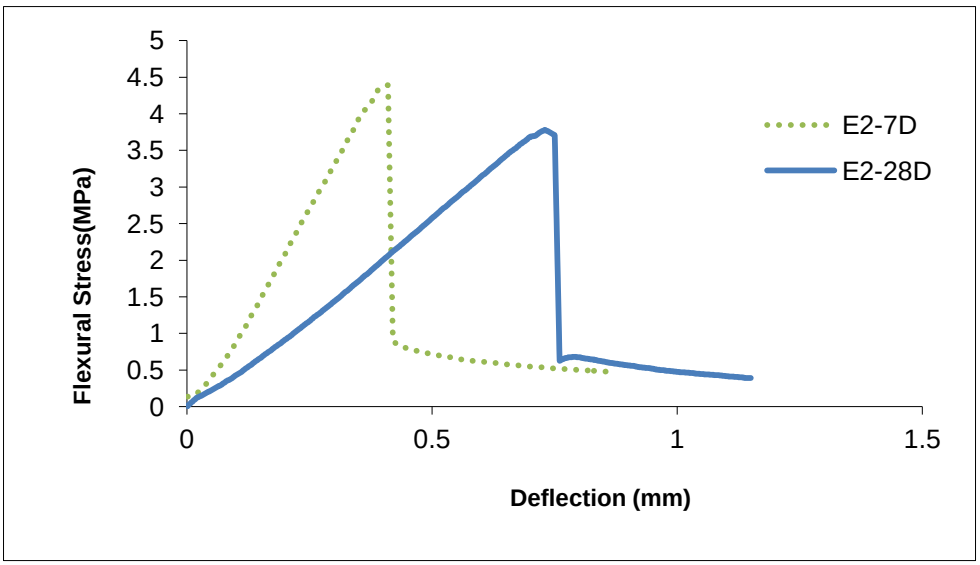

Figure 5-2 Flexural behaviour of FCB reinforced by 2% eucalyptus fibres (7 & 28 days)

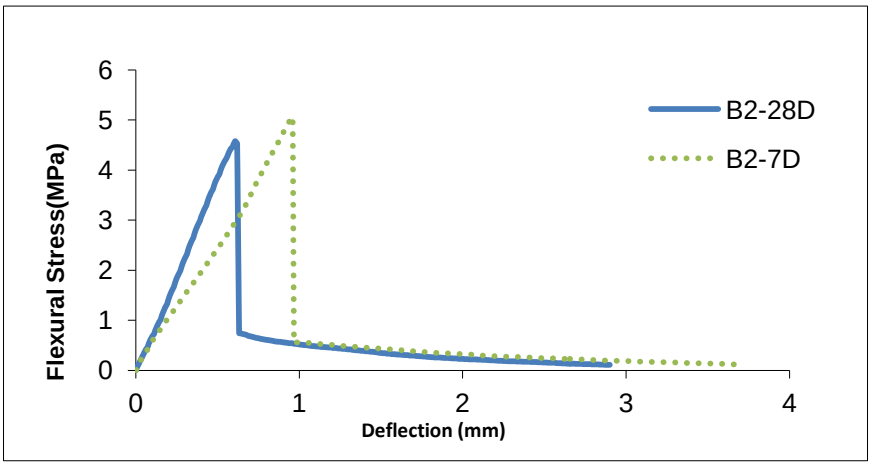

Figure 5-3 Flexural behaviour of FCB reinforced by 2% bagasse fibres (7 & 28 days)

As observed, there are three important points in these figures as follows:

The flexural strength of specimens reinforced by bagasse fibres is a bit higher than specimens reinforced by eucalyptus and wheat fibres.

Almost all groups have brittle behaviour so that, after the maximum point, their strength decreases dramatically.

The flexural strength for 28-day specimens is less than 7-day specimens.

It seems the performance of bagasse in FCB is better than eucalyptus and wheat fibres. Also, specimens reinforced by 2% fibre content cannot lead to flexible or ductile FCB. Also, decreasing the flexural strength during the time (comparing the results of 7 and 28 days) shows that it may cause a harmful chemical or physical reaction within composite ingredients. This will be discussed in the following pages.

For further investigation, FCB was reinforced by 4% fibre content and the results are shown in figures 5-4, 5-5 and 5-6.

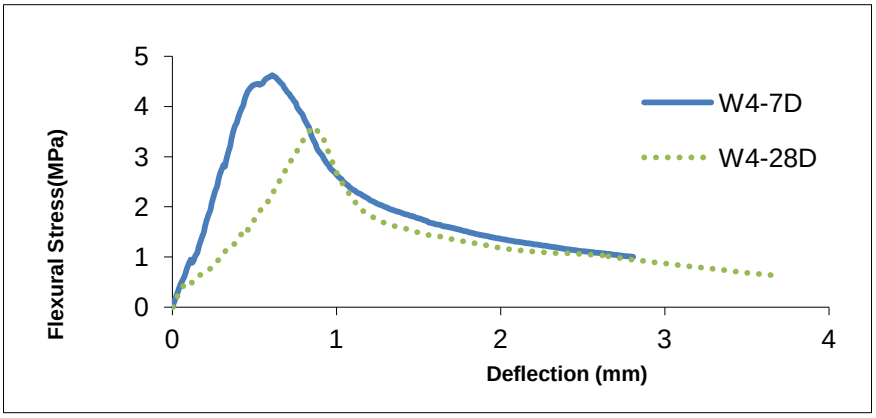

Figure 5-4 Flexural behaviour of FCB reinforced by 4% wheat fibres (7 & 28 days)

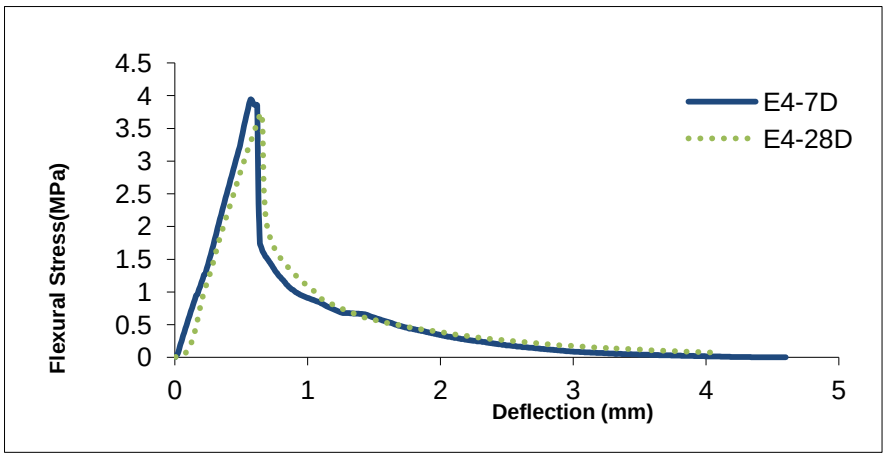

Figure 5-5 Flexural behaviour of FCB reinforced by 4% eucalyptus fibres (7 & 28 days)

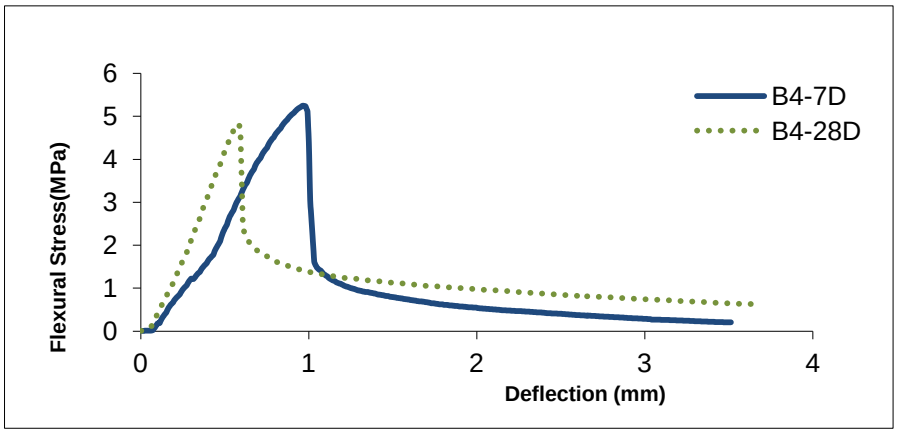

Figure 5-6 Flexural behaviour of FCB reinforced by 4% bagasse fibres (7 & 28 days)

Investigation into figures 5-4, 5-5 and 5-6 shows that FCB reinforced by 4% fibre content has characteristics almost similar to FCB reinforced by 2% fibre content. In other words, the flexural strength of 7-day specimens is higher than that of 28-day specimens. Brittle fracture is still

observed and the flexural strength of FCB reinforced by bagasse fibres is more than those reinforced by the two other fibres.

The reduction in the flexural strength of 28-day specimens in comparison to 7-day specimens may relate to the presence of lignin in the fibres (Morteza et al., 2011). As these fibres are obtained from agricultural waste products by a mechanical method of fibre production, there is residual lignin (more than 60% as already mentioned in section 3.1.3) which interferes with the hydration process of cement.

During the hydration of cement, calcium hydroxide is produced and the pH becomes more than 12. While the inherent characteristics of plant fibres are generally acidic in nature, there will be some change in the pH of the system which may change the solubility and stability of the hydrated compounds and, as a result of this reaction, the alkaline pore water dissolves the present lignin and hemicellulose in the middle lamellae of the fibres, hence weakening the link between the individual fibre cells and fibre-matrix interface.

Romildo et al. (2000) showed that the produced alkaline products attack hemicellulose and lignin present in fibres, particularly when the amount of lignin is greater than 30%. The alkaline hydrolysis of hemicelluloses and lignin results in the formation of calcium salts of lignin, polysaccharides and certain reducing sugars. This dissolved or precipitated salt has adverse effects with the subsequent hydration of cement and causes degradation of molecular chains, therefore leading to a reduction in the degree of polymerisation and lower tensile strength.

To understand the effects of types of fibre and the amount of fibre content, the results of flexural strength (28 days) for all types of fibre are illustrated in figures 5-7 and 5-8. In these figures, the control specimen is a cement board without any fibres.

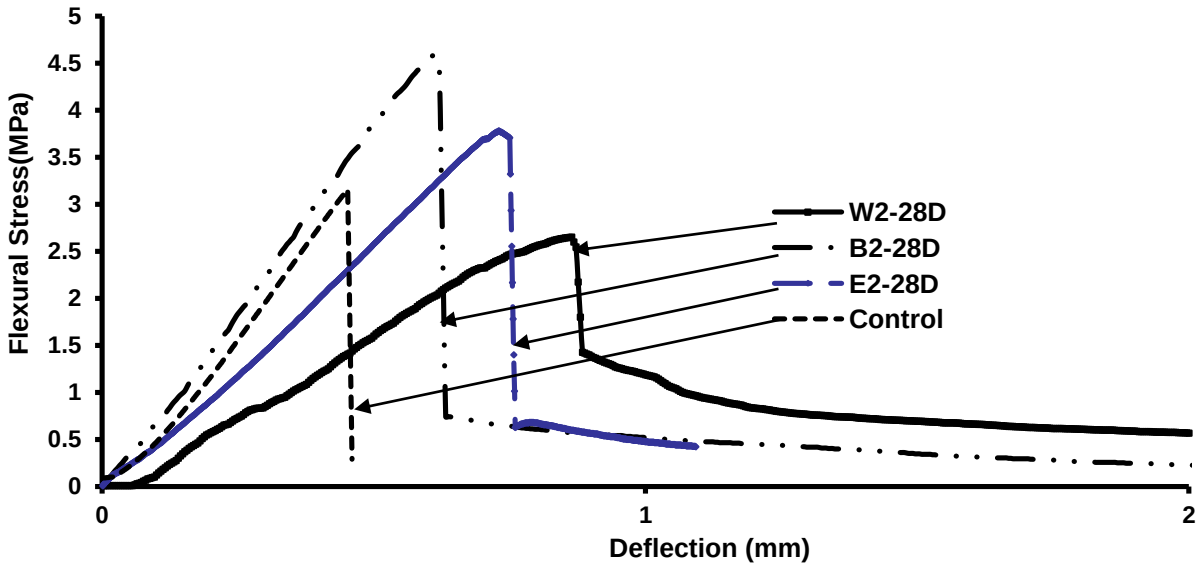

Figure 5-7 Flexural behaviour of FCB with 2% fibres and compared with control specimen (28 days)

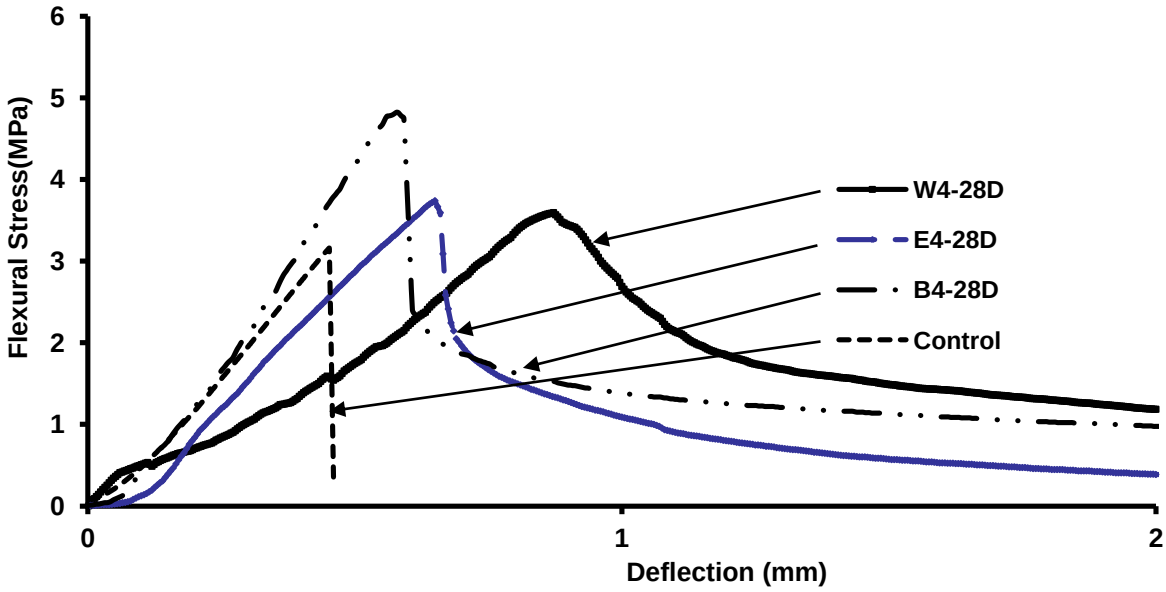

Figure 5-8 Flexural behaviour of FCB with 4% fibres and compared with control specimen (28 days)

For each section of this chapter, all observations in the laboratory and graphs are described then a comprehensive discussion is presented.

Observation

As observed in Fig. 5-7, adding 2%fibres leads to some changes in flexural behaviour but all of them are still as brittle as the control specimen. The flexural strength for the control specimen is 3.1 MPa and strengths for the specimens, i.e. W2, E2 and B2, are 2.6, 3.7 and 4.8 MPa respectively. Except W2, other specimens, particularly B2, shows an increase in flexural strength.

Increasing to 4% fibres in the specimens changed the flexural behaviour considerably in comparison to the control specimen. Not only did all groups have the maximum flexural strength more than the control ones but also their ductility was improved.

To summarize the results of the flexural strength of FCBs reinforced by wheat, eucalyptus and bagasse fibres, the average of the calculated maximum for each group is shown in figure 5-9.

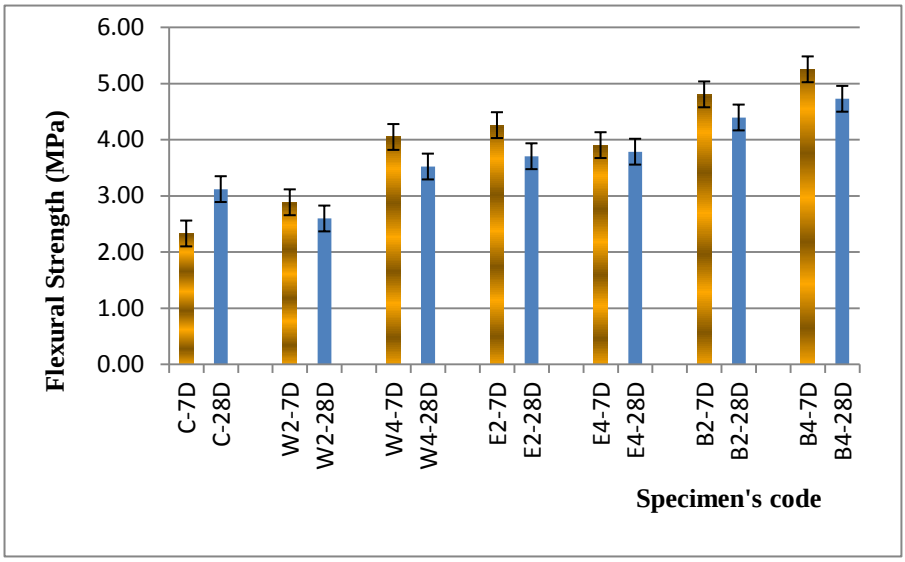

Figure 5-9 Average of flexural strength of FCB reinforced by wheat, eucalyptus and bagasse (7 & 28 days)

As can be seen, the flexural strength of B4 is more than that of other groups. After bagasse, the highest flexural strength is related to E4 and W4 respectively.

Increasing the bagasse fibre content from 2 up to 4% enhanced the maximum flexural strength of the control specimen by 50 to 60 percent respectively. Increasing the eucalyptus fibre content to 4% increased the flexural strength of the control specimen by around 35%. And 4% fibre content of wheat fibres increased the flexural strength of the control specimen by around 20%.

Increasing the fibre content to more than 4% caused a disruption in the manufacturing process. As a result of the low specific gravity of fibres it caused the fibres to float on the top of the slurry so that non-uniform distribution of fibres in the matrix occurred. Hence, the top surface of the composite was filled by accumulated fibres. Consequently, making specimens with greater than 4% fibre content was ceased.

Discussion

Better performance of the bagasse fibres can be attributed to the high tensile strength and the high aspect ratio of the bagasse fibres in contrast to the wheat and eucalyptus fibres. The high aspect ratio of the fibres leads to an increase in the lateral surface area of the fibres contacting with the cement, hence bonding between the cement and the fibres increases. Also, the high tensile strength of the fibres causes a change in the mechanism of rupture from breaking fibres to pulling up the fibres from the matrix. This means that the bonding strength between the cement and the fibres controls the mechanism.

The flexural behaviour of the composite containing the wheat fibres is also illustrated in figure 5-7 and 5-8.

As can be seen, adding 2% of fibres causes a reduction in the flexural strength compared to the control specimen, while increasing to 4% of these fibres enhances the flexural strength a bit more than the control specimen. After analysing the broken pieces of the specimens, it was observed that some parts of the wheat fibres couldn’t distribute uniformly in the matrix and quantities of these fibres clamped together and were placed in some points of the specimen. This meant some areas of the specimens were without fibres. This could lead to growth of the initial cracks in

these areas. When the amount of the fibres reached up to 4%, the fibres covered the whole of the composite; however, the 'balling effect' was still observed in some points of the composite. This means a minimum amount of fibres have been distributed in the whole composite. It seems this returns to the inherent characteristics of wheat fibres, i.e. they attract each other.

Another point than can be deduced from figure 5-8 is that applying 4% fibre content of the wheat or eucalyptus fibres causes an insignificant rise in maximum flexural strength compared to the control specimen; however, its effect on energy dissipation (or ductility) is considerable. It seems the reasons for the characteristics of W4 and E4 are different from each other (figures 5-10 and 5-11). The average and minimum tensile strength of the wheat fibres are 6 and 4 MPa respectively (table-3-1). As it can be observed in figure 5-8, when the maximum flexural strength of W4 approaches 4 MPa, the specimen starts gently breaking. Because some weak fibres with minimum tensile strength (4MPa) may have been placed in the matrix, they reach the maximum capacity of tensile bearing then break and the initial cracks appear in the specimen. Once, some parts of the specimens encounter cracks, the applied stress for the rest of the specimen increases. Since there are some strong fibres in the specimen, loading can continue and breaking would happen softly. Observation of the broken specimens confirms (fig. 5-10) that most of the wheat fibres had been broken rather than being pulled up from the matrix. This type of behaviour for the wheat fibres can also lead to more ductility, as shown in figure 5-8, because breaking fibres comes about gradually and it will increase the ductility of the specimens.

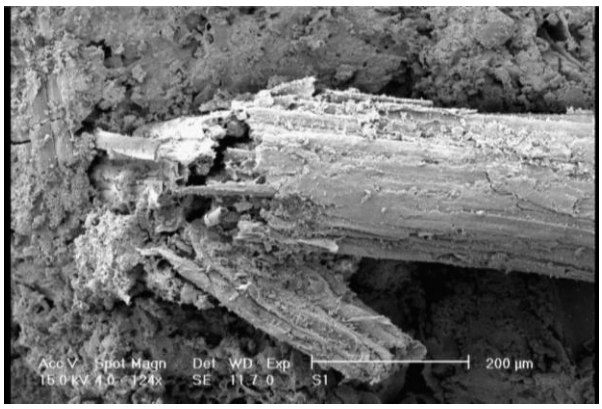

Figure 5-10 Breaking of wheat fibres in loading

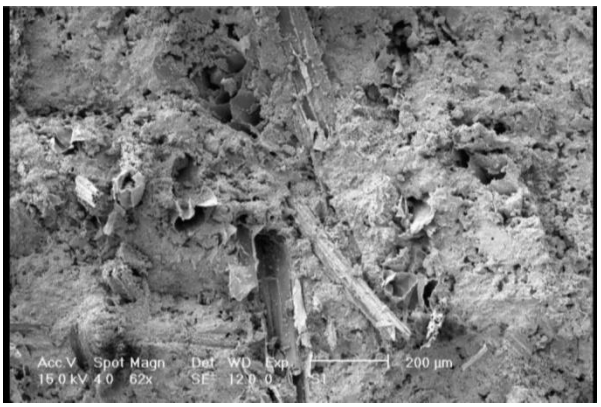

Figure 5-11 Pulling out of eucalyptus fibres from composite

As figures 5-10 and 5-11 show there are different mechanisms of rupture in W4 and E4. The reason for specimens reinforced by eucalyptus fibres breaking seems not to be related to the weak tensile strength of the eucalyptus fibres. As can be seen (figures 5-7 and 5-8), applying 2 or 4% fibres doesn't have any important effect on flexural behaviour of the composites. In other words, maximum flexural strength and ductility for both groups are similar to each other. The reason can be attributed to the aspect ratio of these fibres. The aspect ratio for the eucalyptus fibres is 2.3 while those for the wheat and the bagasse fibres are 3.5 and 3.7 respectively. This means the little amount of lateral surface area of the eucalyptus affects bonding between cement and the fibres. Observation of the broken specimens (fig. 5-11) shows that most of the eucalyptus fibres slipped and were pulled out rather than breaking. A slide of fibres occurs suddenly and rapidly so it is not expected for these specimens to show great ductility or energy dissipation. Figures 5-7 and 5-8 and observations of broken samples confirm this declaration.

5.2.1.2 kraft pulp fibres

In addition to wheat, eucalyptus and bagasse fibres, another type of cellulose fibre was investigated in this research. These were kraft pulp fibre, which is obtained from waste cardboard. All details of these fibres and the method of pulping in the laboratory are presented in 3.1.

Although wheat, eucalyptus and bagasse fibres were not suitable to be used with more than 4% fibre content in fibre cement board, the kraft pulp fibres had an appropriate compatibility with the cement matrix and had a good potential to be used with up to 14% fibre content. After manufacturing some specimens in the lab and analysing the primary results, it was decided to do further investigation on this fibre. To this end, specimens reinforced by 1 up to 14% with increments of 1% were made and analysed.

Figure 5-12 shows the average maximum flexural stress experienced by all specimens in each group. This shows that the maximum flexural stress (known as modulus of rupture (MOR)) gradually increases as fibre content is increased for all specimens.

Observation

The standard deviations of the results of flexural test were between 0.14 and 0.25 MPa, indicating the data points tend to be very close to the mean. In other words, the experimental test results could be reliable and this value of standard deviation occurred due to standard errors. Error bars shown in figure 5-12 also confirm the reliability of the gained results.

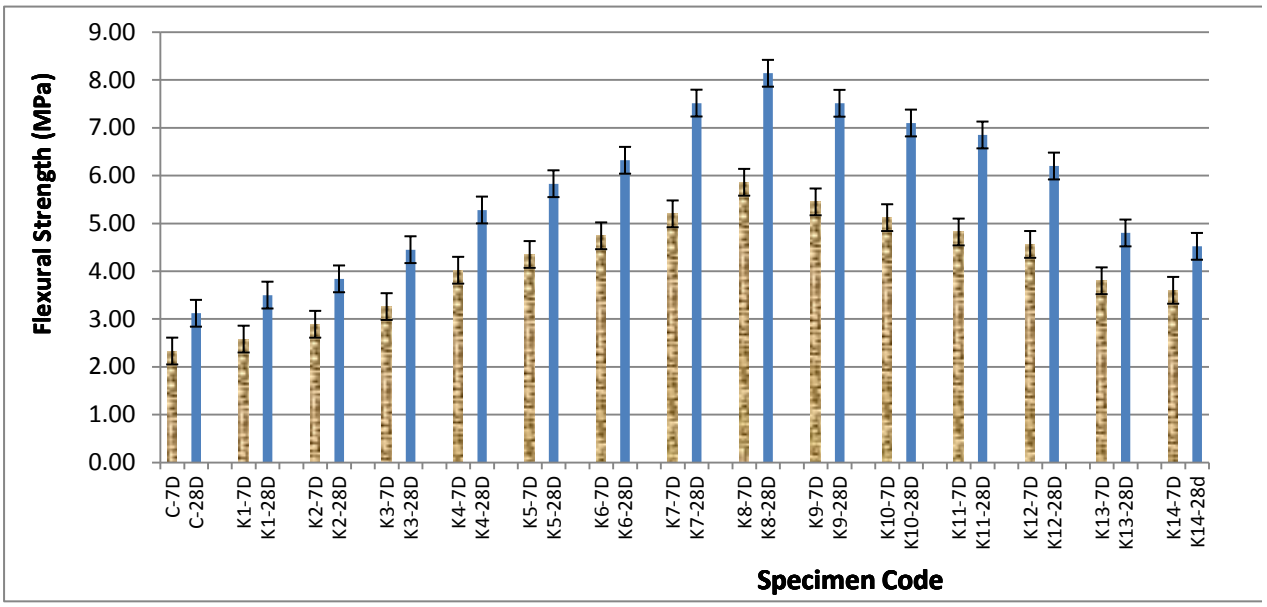

Figure 5-12 Flexural strength of FCB reinforced by different amounts of kraft pulp fibres (7 & 28 days)

There are several important points in figure 5-12 as follows:

1- As can be attested in figure 5-12, with an increase in the fibre content up to 8%, flexural strength approximately increases regularly and adding fibre content of more than 8% leads to an approximately regular reduction in flexural strength. In other words, the optimum percentage of fibre content of the kraft pulp fibres for reinforcing fibre cement board is 8%.

2- Unlike the other previously studied fibres (wheat, eucalyptus and bagasse), in all mixes with kraft pulp fibres the flexural strengths of 28-day specimens were more than 7-day ones.

3- When increasing the fibre content between 2 and 8%, flexural strength increases dramatically but when increasing fibre content between 8 and 14%, flexural strength decreases slowly.
4- Differences between 7-day and 28-day flexural strengths for specimens reinforced by 7 up to 11% fibre content were more than those for other mixes.
5- The highest flexural strength of FCB, related to K8, was 260% more than the control specimens.

As already described, to clarify the flexural behaviour of the specimens with different amounts of fibre content, one in five specimens was selected (as they are approximately similar to each other) and diagrams of flexural strength versus deflection at the middle of the specimen were drawn. In order to avoid confusion due to an excessive number of graphs, only some mixes have been chosen and their flexural behaviour is described.

Figure 5-13 shows the 28-day flexural behaviour of K2, K4, K6 and K8, and figure 5-14 illustrates the 28-day flexural behaviour of K8, K10, K12 and K14.

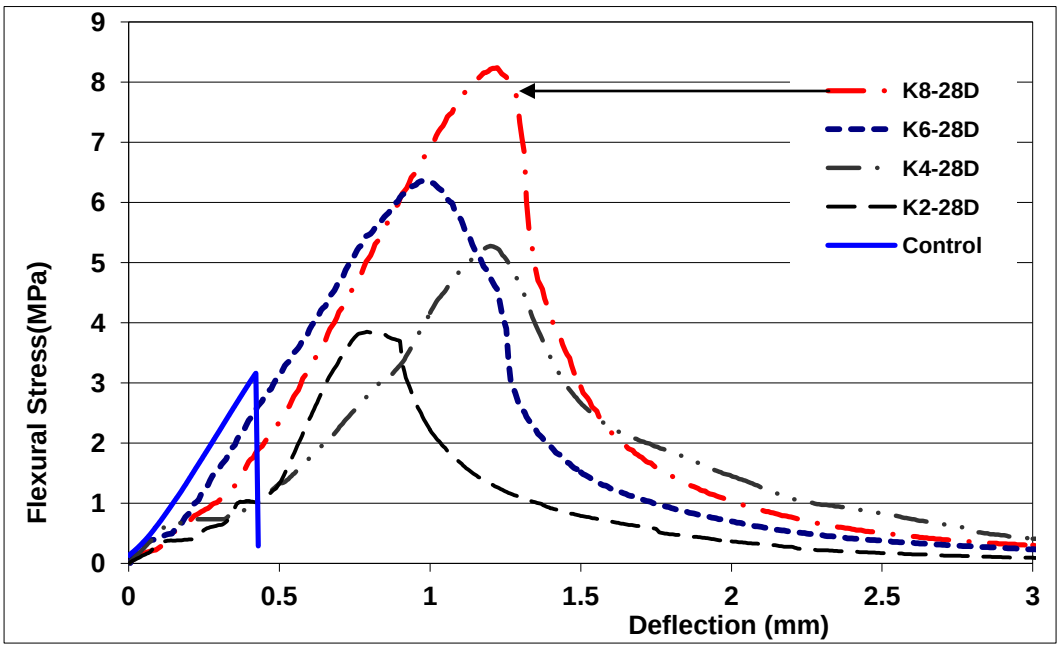

Figure 5-13 Flexural behaviour of FCB reinforced by 2, 4, 6 & 8% of kraft pulp fibres (28 days)

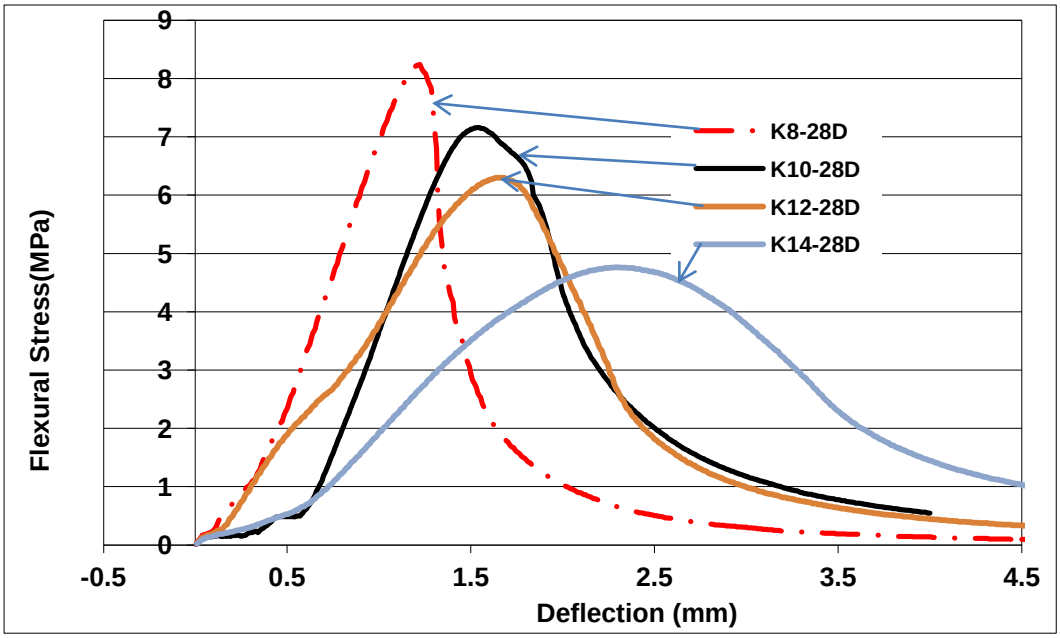

Figure 5-14 Flexural behaviour of FCB reinforced by 8, 10, 12 & 14% of kraft pulp fibres (28 days)

Discussion

As already expressed in 5.2.1, the most important reason for reduction of flexural strength between 7 and 28 days for FCB reinforced by wheat, eucalyptus and bagasse was related to the presence of a large (≈ 60%) quantity of lignin. In the kraft pulp fibres, there is a small amount of lignin (less than 10%) because these fibres are obtained from waste cardboard. Cardboard is manufactured by cellulose fibres which have been produced by a chemical process. In the chemical process for the production of wood pulp a solution of caustic soda and sodium sulphide is usually employed as the liquor in which the pulpwood is cooked in order to loosen the fibres. In the kraft process most of the lignin originally presents in the wood is removed, whereas mechanical pulping processes leave most of the lignin in the fibres.

In addition to the small quantity of lignin, the aspect ratio of the kraft pulp fibres is considerably much greater than the previously studied fibres. The cross-section of the kraft fibres is rectangular and is approximately 22 micron wide and 5 micron high. This means the aspect ratio for this type of fibre could be estimated by an equivalent circle cross-section of around 9 micron in diameter. Since the average length of the kraft fibres is around 0.87 mm (from table 3-1), the aspect ratio of these fibres is around 90. This big aspect ratio provides great bonding within hydrated cement particles and fibres.

The kraft pulp fibres have an appropriate potential for uniform dispersion in the cement matrix. This may relate to the inherent characteristics of this type of fibre such as density, ability to fibrillate and bonding with cement particles.

The specimens reinforced by 8% pulp demonstrated MOR 8.5 MPa, which is more than 2.5 times as high as the control specimens. These specimens are classified in class 2 in the BS EN 12467 -07 classifications.

The presence of fibres in the cement matrix could enhance its mechanical properties such as tensile and flexural strength, energy dissipation and ductility. This is because fibre characteristics such as high tensile strength, length and aspect ratio make fibres as bridge over cracking. If there is an appropriate bonding between cement and fibres, it is expected that with increasing fibre content, the flexural strength of FCB increases. So by increasing the fibre content from 1 to 8%, the flexural strength increases. The reason for the reduction of flexural strength when fibre content exceeds 8% is related to two issues. The first one is the 'balling effect', which means fibres clamp together and this leads to some weak point being created in the composite. The second one is related to the acceptance capacity of the cement matrix. This means

there is a balanced condition between cement and cement particles. For instance, each fibre should be confined by enough hydrated cement particles; when the number of fibres increases, the amount of hydrated cement particles is not enough to cover all lateral surfaces of the fibres and consequently a disruption occurs in the composite.

In addition to aforementioned issues, kraft pulp fibres have many fibrils around the main fibres. The microstructure study of this type of fibre is illustrated by an SEM photo in figure 5-15. As observed, the presence of numerous fibrils around the outer surface of the main fibre can increase friction and bonding within the fibre-cement interfacial zone.

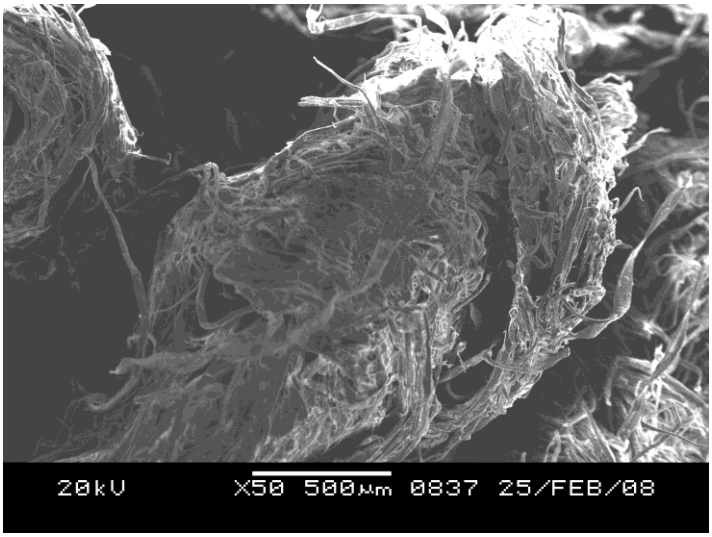

Figure 5-15 SEM photo of kraft pulp fibre

5.2.2 Blending of natural waste and synthetic fibres

In the first stage of this research, the effect of natural fibres on mechanical property of FCB was investigated. The results show that FCB reinforced by the kraft pulp fibres had better flexural behaviour in comparison with wheat, eucalyptus and bagasse. Therefore, the next stage of research was concentrated on blending the kraft pulp paper and synthetic fibres. Based on the conducted research and reviewed literature, the following mixes were chosen for the next stage of the research.

N.B. FCBs reinforced by 2, 4, 6 and 8% of kraft pulp fibres were called K2, K4, K6 and K8.

5.2.2.1 Effect of polypropylene fibre

As the best result of the previous stage was related to K8, 8% kraft pulp fibres was selected as a reference natural fibre mix and different percentages of polypropylene fibre were added to the composite and their flexural behaviours were investigated.

The polypropylene fibres were chosen in two different lengths 3mm and 6mm. Lengths of more than 6mm were not selected because primary laboratory manufacturing specimens showed that fibres with lengths of more than 6mm cannot disperse uniformly in the cement matrix; not only do they clamp together but also the processing control of making specimens is disrupted and the specimen surface would be uneven. Also, adding more than 1.5% of polypropylene fibres in the mixes was impossible because the fibres were accumulating on top surface of the specimens, resulting in an uneven surface.

The properties of polypropylene and proportion of materials used in the mixes are given in table 3-2 and table 4-2 respectively.

Before investigation into the flexural behaviour of these specimens, the average flexural strength for all specimens in each group is shown in figure 5-16.

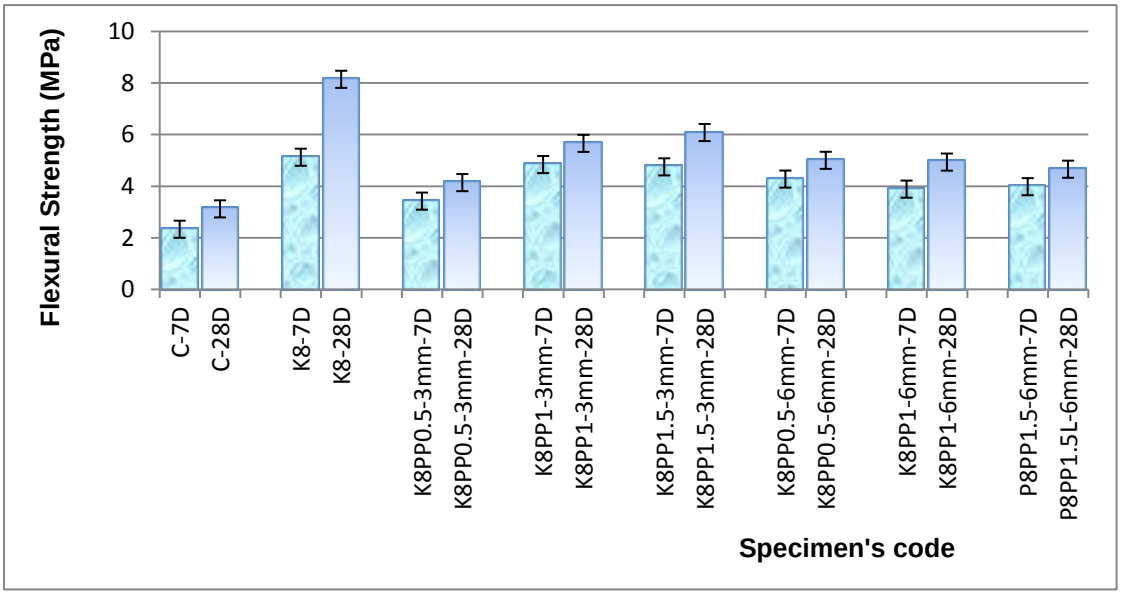

Figure 5-16 Flexural strength of FCBs reinforced by kraft and polypropylene fibres

From figure 5-16 the following points can be deduced:

1- Adding polypropylene fibres to FCB reinforced by kraft pulp fibre leads to a decrease in flexural strength. The reduction value is between 35 and 95% depending on the amount and length of the polypropylene fibres. However, there is a general reduction in flexural strength when polypropylene fibres are added to FCB reinforced by kraft pulp fibres. There are two points to this trend as follows:

   1-1 By increasing the amount of 3 mm polypropylene fibres, from 0.5 up to 1.5%, flexural strength increased from 4 to 6 MPa.

   1-2 By increasing the amount of 6 mm polypropylene fibres, from 0.5 up to 1.5 percent, flexural strength decreased from 5 to 4.6 MPa.

2- For all mixes, 28-day flexural strength is higher than 7-day.

3- Applying polypropylene (PP) fibres 6 mm in length caused a reduction in the flexural strength of K8 compared to applying 3 mm PP fibres.

For further investigation on the flexural behaviour of FCB reinforced by PP, the effects of adding PP in mixes are illustrated in figures 5-17 to 5-20.

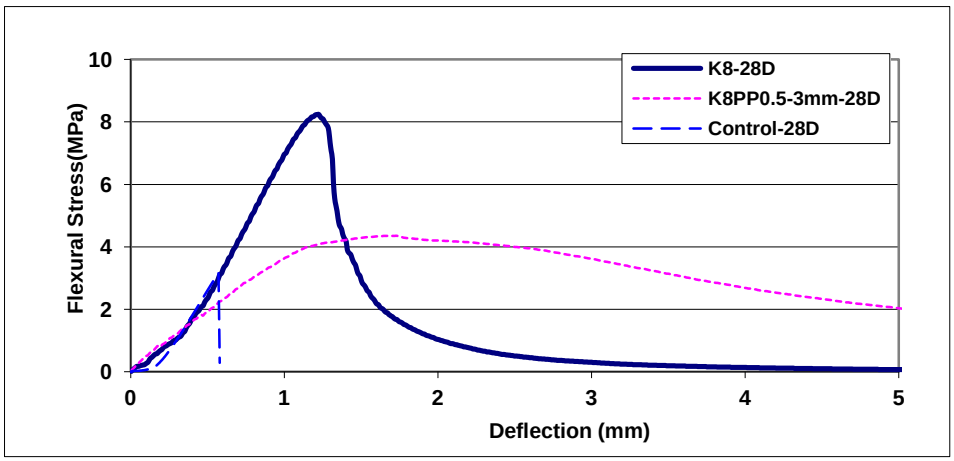

Figure 5-17 The effect of adding 0.5% PP (3mm) on flexural strength (28 days) of FCB reinforced by 8% kraft fibres

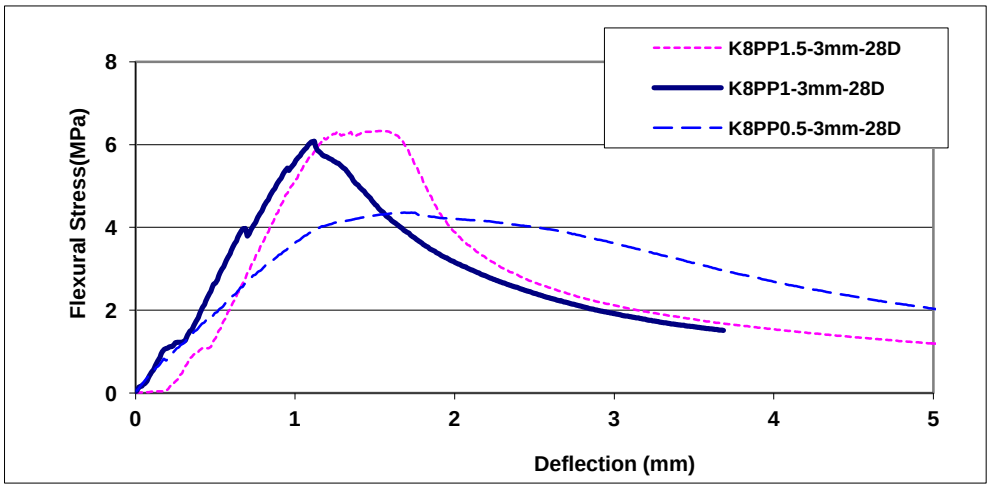

Figure 5-18 Flexural behaviour (28 days) of FCB reinforced by 8% kraft and 0.5, 1 & 1.5% PP fibres (3mm)

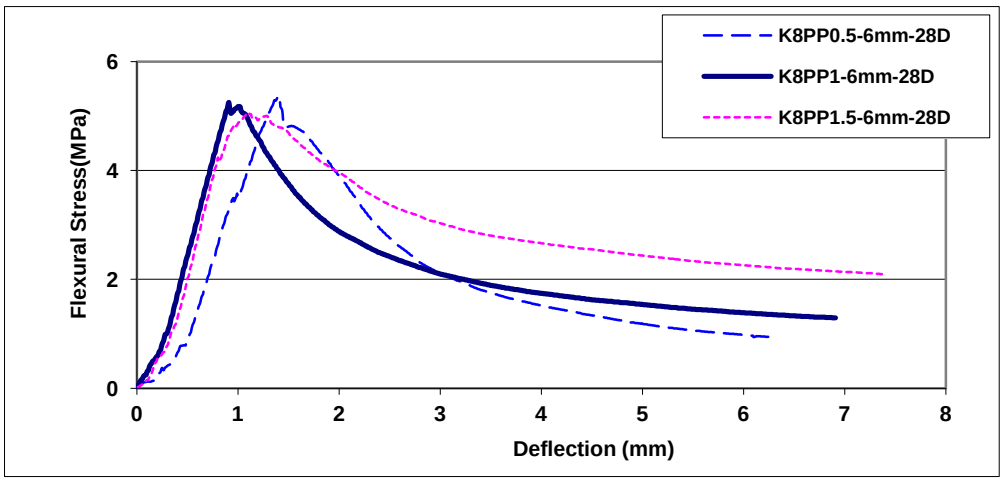

Figure 5-19 Flexural behaviour (28 days) of FCBs reinforced by 8% kraft and 0.5, 1 & 1.5% PP fibres (6mm)

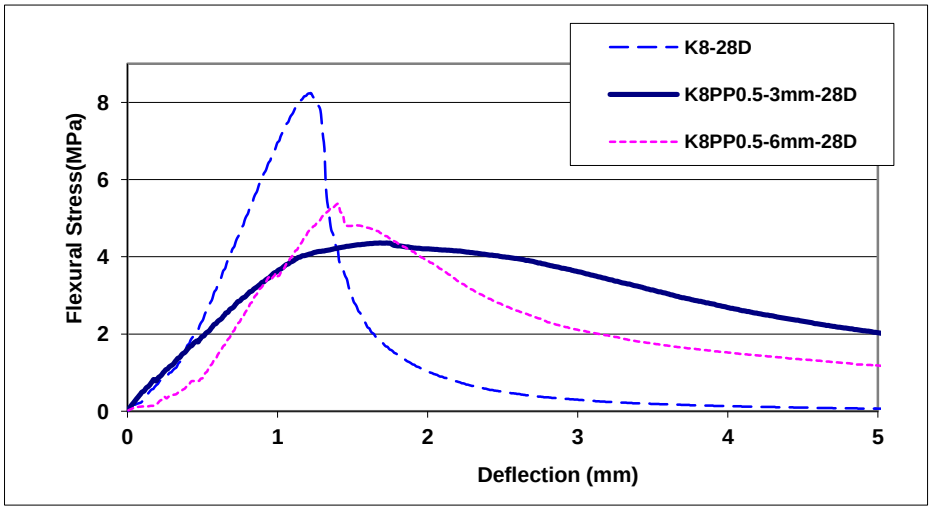

Figure 5-20 Comparison of 3mm & 6mm PP fibres on flexural behaviour of FCB reinforced by 8% kraft fibre

In figure 5-17, the decrease in flexural strength and increase in area under the curve and ductility of FCB reinforced by 8% kraft pulp fibre and 0.5% PP fibres with lengths of 3mm are depicted. Also in this figure, the control specimen (neat cement without any fibres) is demonstrated.

Figure 5-18 shows that, when increasing the 3mm PP fibre content from 0.5 to 1.5%, the flexural strength of FCB increases but the flexural strength of FCB reinforced by 1 or 1.5% PP is approximately equal.

Unlike for 3mm PP, when 6mm PP fibres are applied with 0.5, 1 and 1.5 % in the mix, no significant difference is observed in flexural strength, ductility and area under the curve of the FCB (fig. 5-19).

In figure 5-20, a comparison is made between 3mm PP and 6mm PP when 0.5% of each one is used in the mix. This comparison shows that the ductility and area under the curve of 3mm PP fibres are a bit higher than of 6mm PP fibres.

To discuss the behaviour of polypropylene fibres in the cement matrix, the characteristics of these fibres should be investigated. These fibres have a cylindrical shape with a smooth surface and there is no fibril on the surface.

Figures 5-21 and 5-22 show SEM images of the polypropylene used.

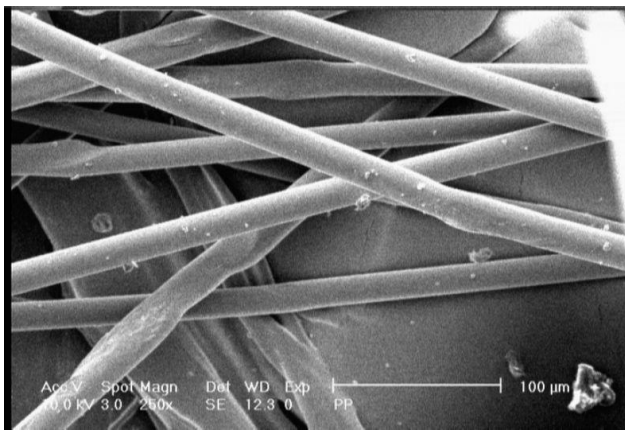

Figure 5-21 Microstructure of the polypropylene used

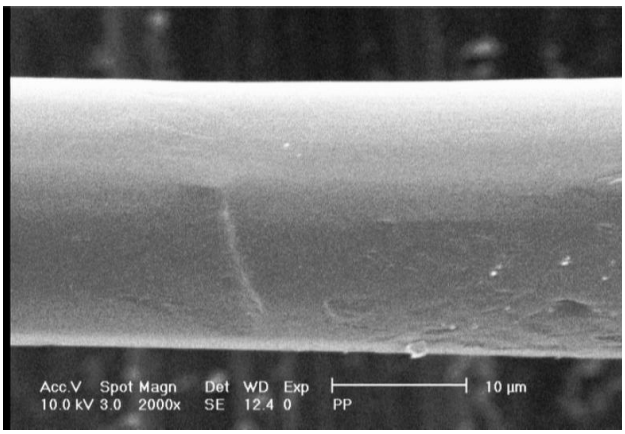

Figure 5-22 Smooth surface of polypropylene with cylindrical cross section

These fibres are not as hydrophilic (wettable) as the kraft pulp fibres. Wetting is the ability of a liquid to maintain contact with a solid surface, resulting from intermolecular interactions when the two molecules are brought together. The degree of wetting (wettability) is determined by a force balance between adhesive and cohesive forces. Wetting is an important factor in the bonding or adherence of fibres to hydrated cement particles. In polypropylene, wetting and the surface forces that control wetting have an important effect on manufactured fibre cement board. This property of polypropylene can be considered as one of the factors that reduce flexural strength. Other important parameters are as follows:

- The density of these fibres (0.9 gr/cm^3) is important because in the manufacturing process these fibres are lighter than other materials (cement, water and the kraft pulp fibres) and they come up and float on the top surface of the specimen. This leads to non-uniform distribution of fibres in the mix resulting in weak points in the specimen.

- The increased flexural strength of specimens reinforced by blending polypropylene and kraft fibres from 7 up to 28 days shows that polypropylene fibres have an appropriate resistance in alkaline media.
- The tensile elongation at break for polypropylene fibres, which can be as much as 15-18% (as shown in table 3-2), can characterize the deformation of specimens reinforced by these fibres, as can be observed in figures 5-17 to 5-20.
- Applying fibres with 6 mm in length creates 'fibre balling' which means fibres clamp together and this disrupts the uniformity of fibres in the mix. When increasing these fibres, no important changes are observed in flexural strength. It seems the maximum capacity of the specimens reinforced by 8% kraft pulp fibres for accepting polypropylene is 0.5%, although clamp incidents are observed with this small amount of fibre content. It means that not only does an excess fibre greater than 0.5 % not contribute effectively in load bearing but also they accumulate on the surface of specimens and clamp events will occur much more than before. In other words, the expected function of using fibres in FCB does not satisfy when fibre content excess is more than the capacity of FCB in confining fibres.

One of the interesting results that can be deduced from figures 5-18 and 5-19 is related to the ability of cement composite to accept polypropylene. When increasing fibre content (PP- 3mm) from 0.5 to 1%, flexural strength increases but excess fibre content of more than 1% (i.e. 1.5%) does not affect flexural strength effectively. When 3mm PP fibres are used, the maximum capacity of this fibre cement to confine PP fibres is 1% because the flexural behaviour of K8pp1-3mm and K8pp1.5- 3mm are similar to each other but when 6mm PP fibres are used the

maximum capacity of this fibre cement to accept PP is 0.5% because the flexural behaviours of FCB reinforced by 0.5, 1 and 1.5% fibre content are close together. Therefore it seems that, when increasing the length of the fibres, the amount of fibre content that can be used in FCB will decrease. This may be due to PP characteristics particularly the low density of PP fibres.

It should be noted that all the characteristics of PP fibres (include low density, circular cross-section, large elongation at break, smooth surface, no fibril and hydrophobic behaviour) and existing equipment (including mould, dimensions of mixer, blade, etc.) led to this behaviour of PP fibres in cement boards, so a combination of all these parameters should be taken into account in analysis. This means that changing some of these parameters may lead to different flexural behaviours of FCB reinforced by synthetic fibres.

Based on the results obtained from this stage of research, polypropylene (with the above mentioned properties and conditions) does not have good potential to be used in blending with the kraft pulp fibres in manufacturing FCB. Further research with different amounts of fibre content of kraft pulp fibres and different fibre content of polypropylene fibres was conducted. The same performances were being approximately repeated and no important or interesting results were obtained, so the rest of analysis and discussion for PP was omitted from this report.

Therefore, an attempt to find another synthetic fibre was made for the next stage of this research. Based on the studied and primary conducted tests described in section 3.1, acrylic fibres were selected. The next section deals with the blending of acrylic fibres and the kraft pulp fibres.

5.2.2.2 Effect of acrylic fibres

The results of the flexural strength against the deflection for representatives of all groups are shown in figures 5-23 to 5-33.

The primary tests and analysis of FCB reinforced by blending acrylic fibres and kraft pulp fibres showed that, in contrast to polypropylene, it has different functions when different percentages of acrylic fibres are blended with different percentages of kraft pulp fibres. This different behaviour led to further investigations that are presented in this section.

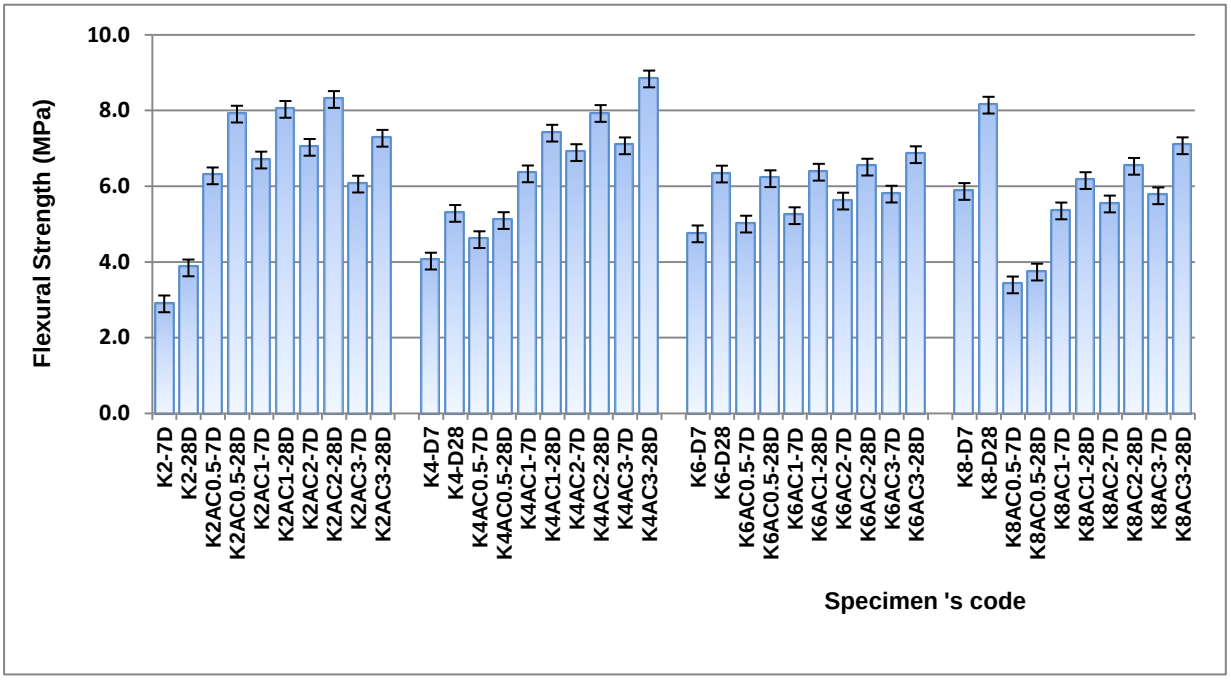

Figure 5-23: flexural strength of specimens (7-day & 28-days) reinforced acrylic and kraft fibres

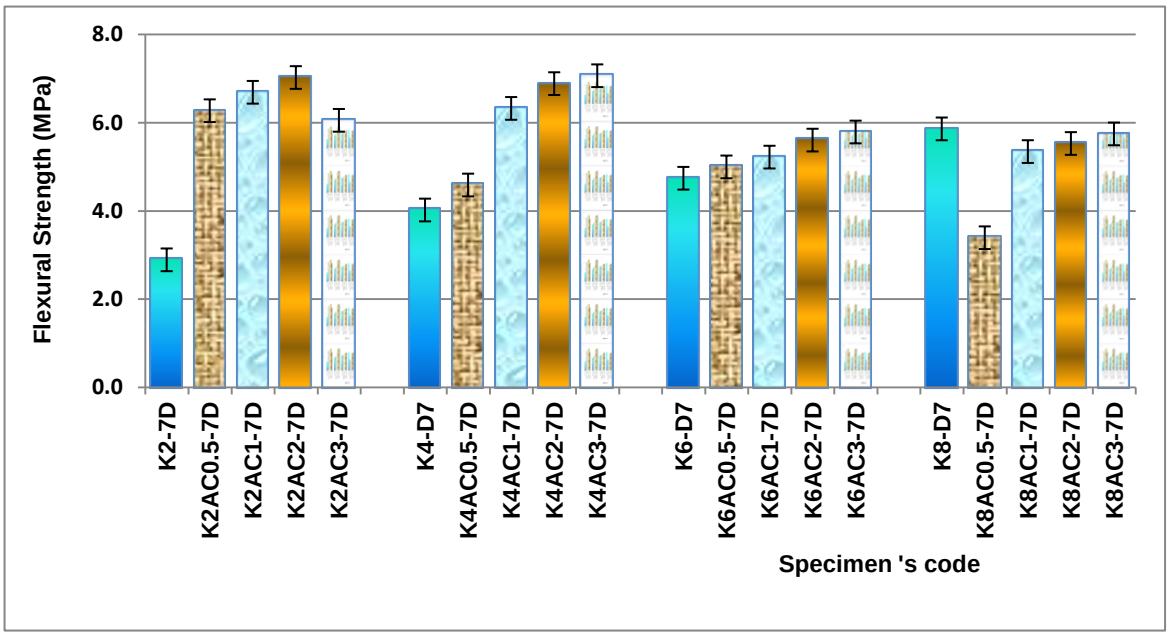

Figure 5-24: flexural strength of specimens (7-days) reinforced acrylic and kraft fibres

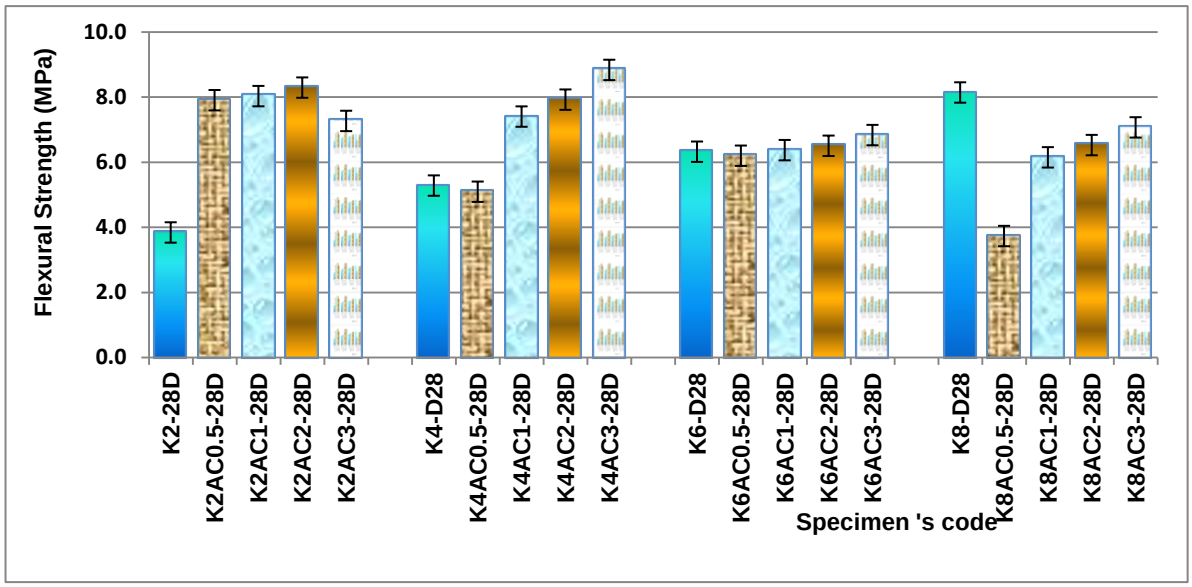

Figure 5-25: flexural strength of specimens (28-days) reinforced acrylic and kraft fibres

Figure 5-23 shows the average flexural strength experienced by the specimens in each group. In 5-23 all the results for the specimens in 7 and 28 days can be compared with each other but in order to make easy understanding and comparing these bar charts, figure 5-24 and 5-25 have been drawn for the 7-day and 28-day flexural strength respectively.

After a deep investigation into figure 5-23 to 5-25, the following points can be deduced:

- The flexural strength of 7-day specimens is less than that of 28-day ones. This means hydration of cement does not have any negative effect on flexural strength. In other words, both acrylic and kraft fibres are resistant in alkaline media.
- In the specimens having a high content of kraft pulp fibres (i.e. K8 and K6), adding acrylic fibre not only does not have a positive effect but also it leads to a considerable reduction in flexural strength.
- In specimens with a low content of kraft pulp fibres (i.e. K2 and K4), adding acrylic fibre has a significant role in raising flexural strength.
- The maximum flexural strength of specimens belongs to K4AC3 and K2AC2 respectively. However, these flexural strengths are not significantly greater than non-synthetic fibre cement board (i.e. K8).

To identify the reasons that may cause these effects, it is necessary to do more investigations into the flexural behaviour of these groups.

Figures 5-26 to 5-29 demonstrate the flexural behaviour of the specimens with constant kraft fibre content but variable acrylic amounts (i.e. 0.5%, 1%, 2% and 3% by the weight of the cement).

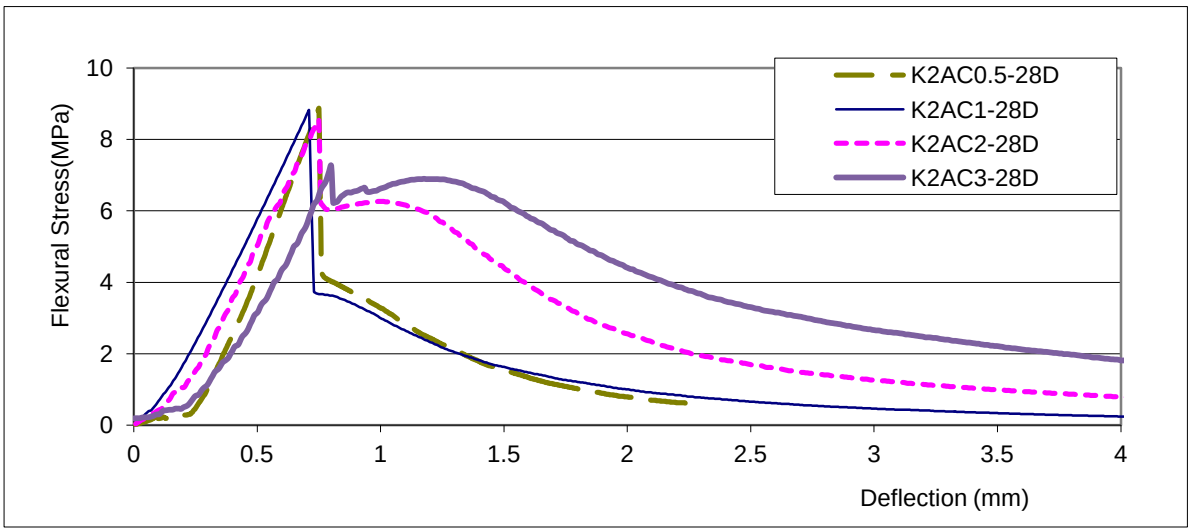

Figure 5-26 Flexural behaviour versus deflection for specimens with 2% kraft pulp fibres and different amounts of acrylic fibres

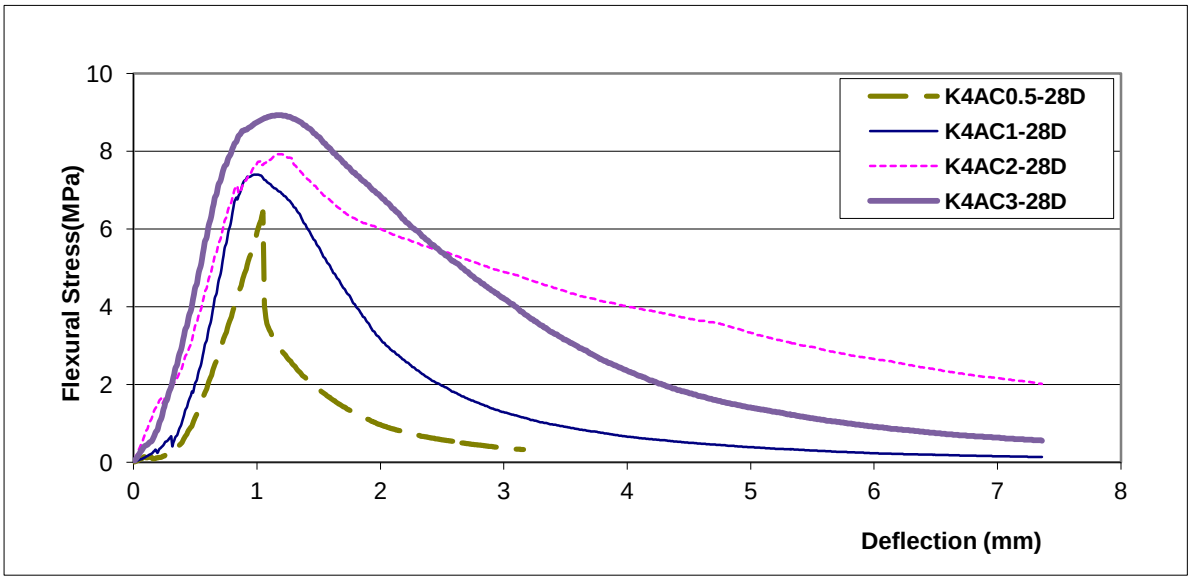

Figure 5-27 Flexural behaviour versus deflection for specimens with 4% kraft pulp fibres and different amounts of acrylic fibres

In figure 5-26 it can be seen that, when increasing acrylic fibres from 0.5 to 2%, no important effect is observed in flexural strength and when the amount of acrylic increases to more than 2%, flexural strength decreases but the area under the curve and ductility of the specimen rise. Also in this graph it can be observed that, except K2AC3, specimens fail at 0.7mm deflection. But the mechanism of K2AC3 is completely different and, in contrast to other specimens which are brittle, it shows a flexible behaviour. In specimens containing 2% kraft fibres, an increase of acrylic fibres from 0.5 to 2% results in slight changes in flexural strength. This is due to the flotation of acrylic fibres in the mix and therefore accumulation of these synthetic fibres on the surface of the specimens. This prevents the uniform distribution of fibres in the mix and is therefore ineffective in improving the flexural strength of fibre cement sheet.

In figure 5-27 all conditions are similar to figure 5-26 and only the constant amount of the kraft fibres is 4%. As can be observed in this graph, the trends of figure 5-26 are repeated but the effect of adding acrylic fibres on increasing flexural strength and area under the curve is more than in figure 5-26.

Based on the above results, 3% of acrylic fibres blended with 4% kraft fibres gives the optimum blended amount for these fibres.

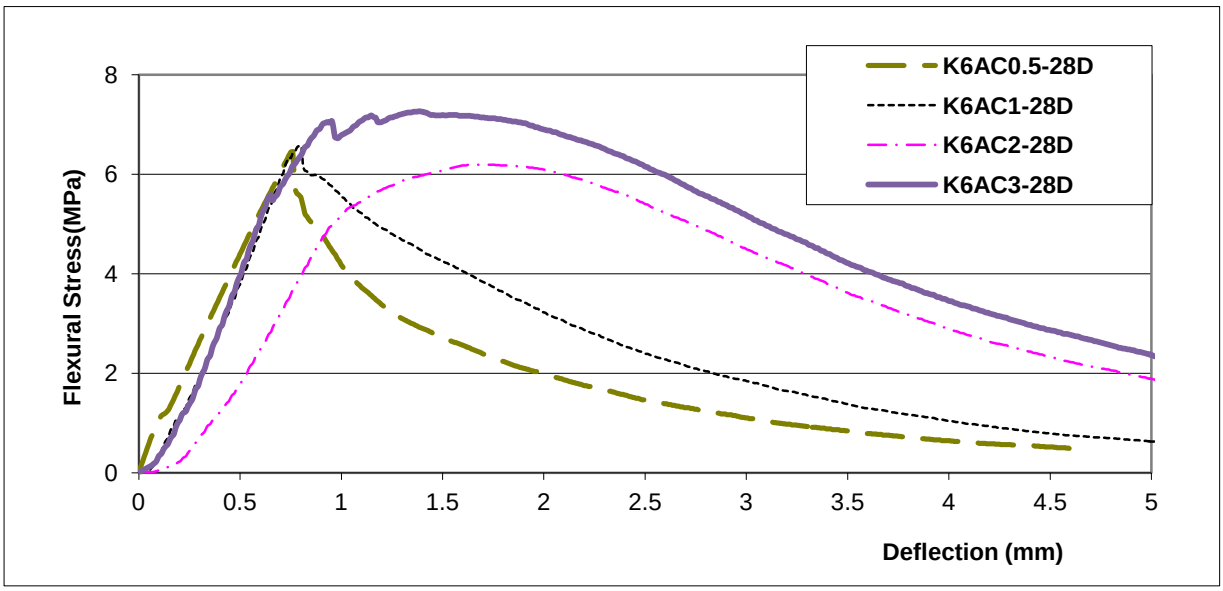

Figure 5-28 Flexural behaviour versus deflection for specimens with 6% kraft pulp fibres and different amounts of acrylic fibres

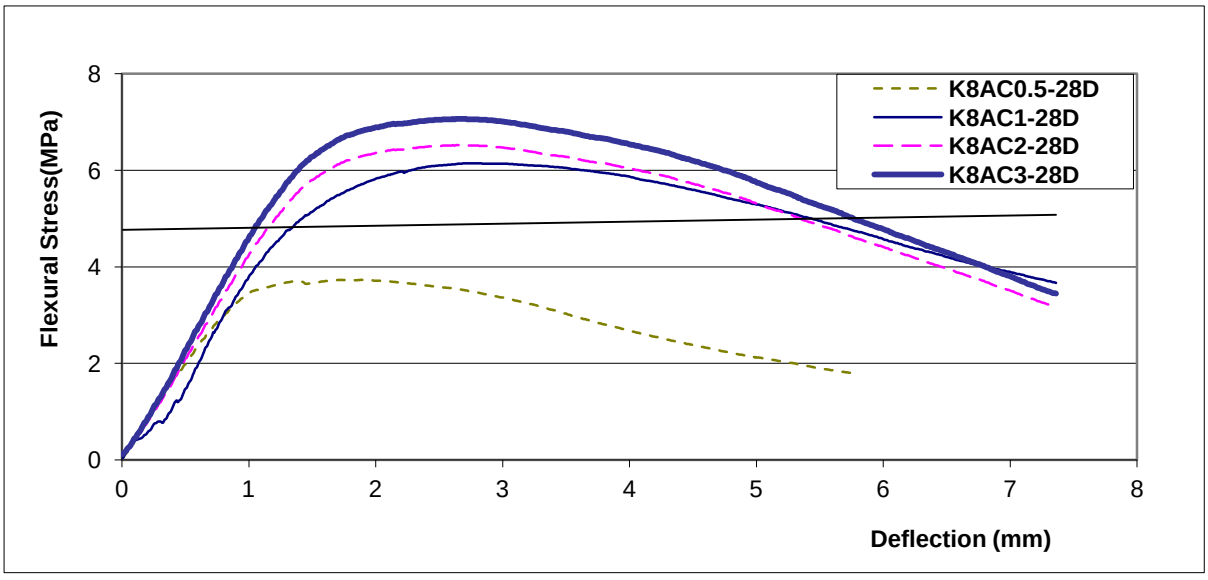

Figure 5-29 Flexural behaviour versus deflection for specimens with 8% kraft pulp fibres and different amounts of acrylic fibres

Figures 5-28 and 5-29 show the flexural behaviour of specimens reinforced by 6 and 8% kraft pulp fibre respectively and the effects of adding acrylic fibre in different amounts (i.e. 0.5, 1, 2 and 3%) are demonstrated in these figures. As can be seen in these figures, the higher the fibre content (including both kraft and acrylic), the tougher the specimens.

Figures 5-28 and 5-29 show that, when total fibre content in FCB increases, a rapid drop in flexural strength isn't observed. The post-crack behaviour of specimens in Figures 5-28 and 5-29 is highly affected by the amount of fibres in the mix. It can be observed that the area below the stress-deflection curve is increased with an increase in the percentage of fibres. In other words, fibres are effective after the composite sheet reaches its maximum strength as fibres act as ties between the two fracture interfaces of the cement matrix and prevent the sudden failure of the samples. This behaviour is due to the great number of fibres so that, in maximum load, when a fibre breaks or pulls out, adjacent fibres come into bearing load with a crack-bridging mechanism so that cracks cannot develop throughout the matrix.

Figures 5-26 to 5-29 show that, when the total fibre content (including both kraft and acrylic fibres) is less than approximately 5%, the effect of blending acrylic and kraft fibres on maximum flexural strength is considerable and in the specimens with a total fibre content of between 5 and 11%, the role of blending fibres on toughness is significant and the flexural strength of specimens is not easily predictable.

So far, the constant fibre content of the kraft pulp fibres versus different amounts of acrylic fibres has been investigated. Another approach in connection with blending acrylic and kraft fibres can be shown in the graphs with constant amounts of acrylic fibre and different amounts of kraft pulp fibres. These graphs are shown in figures 5-30 to 5-33.

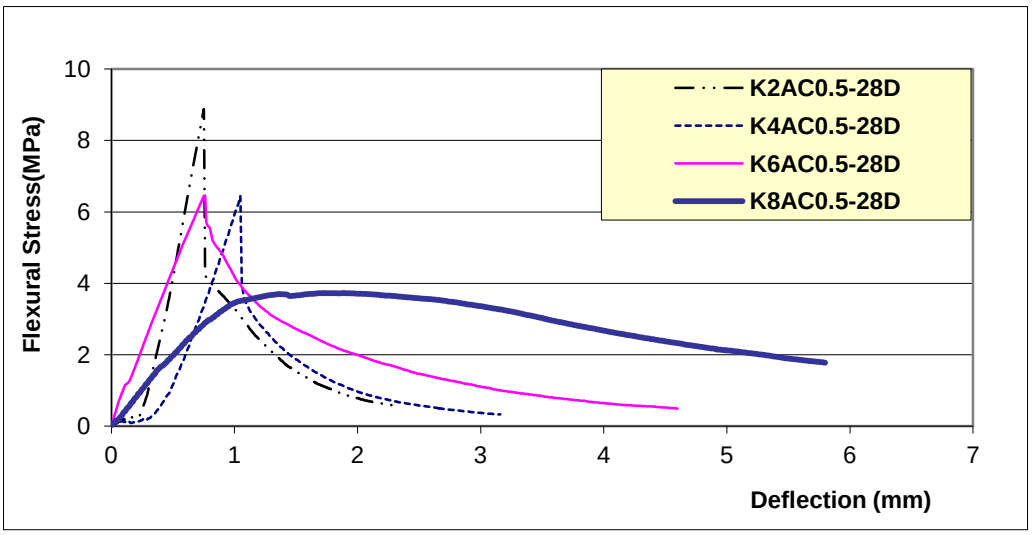

Figure 5-30 Flexural behaviour versus deflection for specimens with 0.5% acrylic fibres and different amounts of kraft pulp fibres

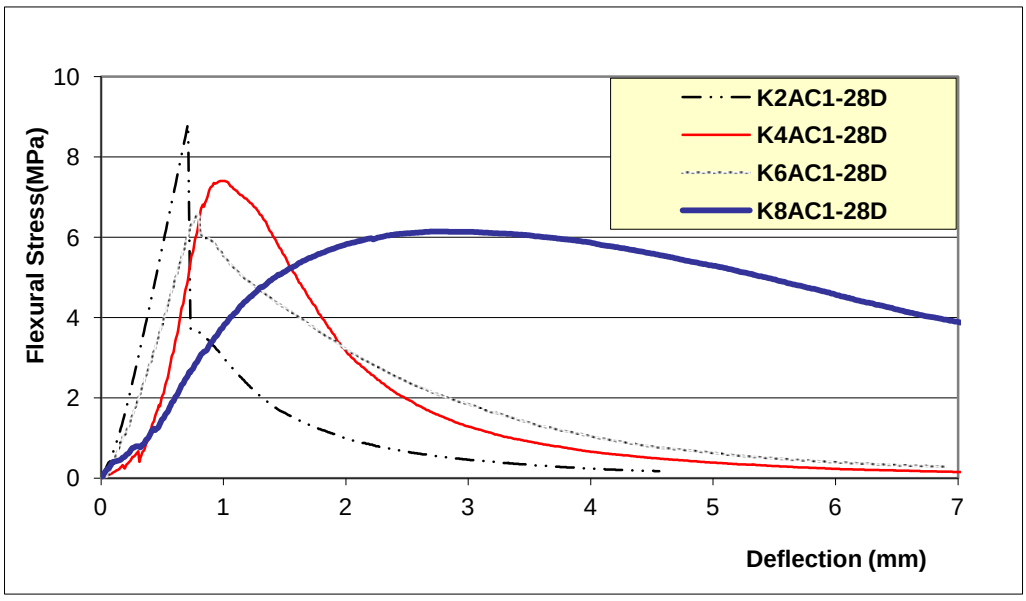

Figure 5-31 Flexural behaviour versus deflection for specimens with 1% acrylic fibres and different amounts of kraft pulp fibres

As can be observed in figures 5-30 to 5-33, for approximately all groups, adding acrylic fibres led to an increase in ductility as a result of increasing fibre content ratio throughout the matrix. But in only a few groups did adding acrylic fibres lead to an increase in flexural strength. It seems there is an optimum amount of acrylic fibre that can raise flexural strength. If the amount of acrylic fibre is close to optimum, interlocking within acrylic fibres, kraft fibres and the hydrated cement matrix would increase. For further investigation of this performance, some important differences between the characteristics of kraft and acrylic fibres should be noted as follows:

- Acrylic fibres don't have any fibril and kraft fibres do.
- Acrylic fibres have weak wettability and kraft fibres have strong wettability.
- The cross-section of kraft fibres is ribbon shaped and for acrylic fibres is bean shaped.
- The specific gravity of acrylic fibres is 1.18 and for kraft fibres is 1.5.
- The length and aspect ratio of acrylic fibres are different to those of kraft fibres.

These differences cause an interaction within the acrylic and kraft fibres in the matrix. In only a few conditions do these characteristics lead to more homogeneity, compatibility and consistency of ingredients to obtain high flexural strength and in other conditions these properties may lead to some disruptions in the mix and consequently lead to a reduction in flexural strength. It seems one of functions of the fibres in fibre cement board reinforced by both synthetic and natural fibres is similar to the effect of aggregate in concrete. If the fine and course aggregates have optimum grading, maximum compressive strength will be gained. In fibre cement, if optimum proportions of acrylic and kraft fibres are applied, the highest flexural strength will be gained.

In optimum conditions, the short kraft fibres and long acrylic fibres are better distributed and the bridging fibres effect shares the load and transfers it to the other parts of the composite, increasing the flexural strength and area under the curve of the composite.

In fibre cement board, finding the optimum proportion of ingredients in the mix is obtained by experimental studies and is not easily predictable. However, it seems that, by increasing the kraft fibre content, the optimum amount of acrylic fibres will increase but an accurate prediction seems to be impossible because not only there are many factors influencing flexural strength but also interactions within those parameters are important.

In the laboratory, adding acrylic fibres of more than 3% of the weight of the cement was impossible because these fibres floated on the slurry and led to a disruption in uniform distribution of fibres and fibres accumulated on the top surface of specimens.

Modulus of elasticity of FCB

In addition to the aforementioned issues in connection with flexural strength and area under the curve, in these figures (figs. 5-30 to 5-33) the elasticity modulus (initial tangent modulus) of specimens can be discussed.

The modulus of elasticity refers to a material's stiffness. It is related to the resistance of an elastic body to deformation by an applied force. Experimentally, the modulus of elasticity, or Young's modulus, is found by determining the slope of the straight line portion of a stress versus strain diagram. In flexural testing, instead of modulus of elasticity which is normally obtained by tension or compression tests , initial tangent modulus is normally calculated by flexural stress-deflection graph. The initial tangent modulus for these composites is investigated in this section.

With excessive loading, the stress-strain curve initially begins linearly, followed by a dramatic change of slope. The phenomena occurring during this sudden change in slope is known as plastic deformation or failure.

For the purposes of finding the initial tangent modulus, the applied stress which should be considered is below the yield point can be chosen. From figures 5-30 to 5-33 it can be observed that the relationship between flexural stress and deflection remains elastic linear up to the maximum flexural stress of the specimens.

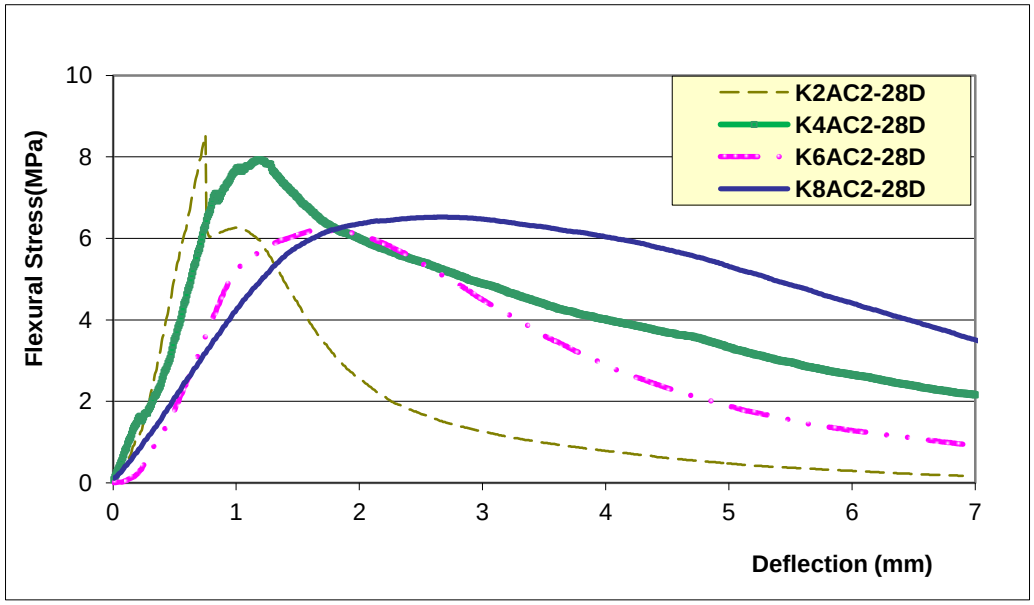

Figure 5-32 Flexural behaviour versus deflection for specimens with 2% acrylic fibres and different amounts of kraft fibres

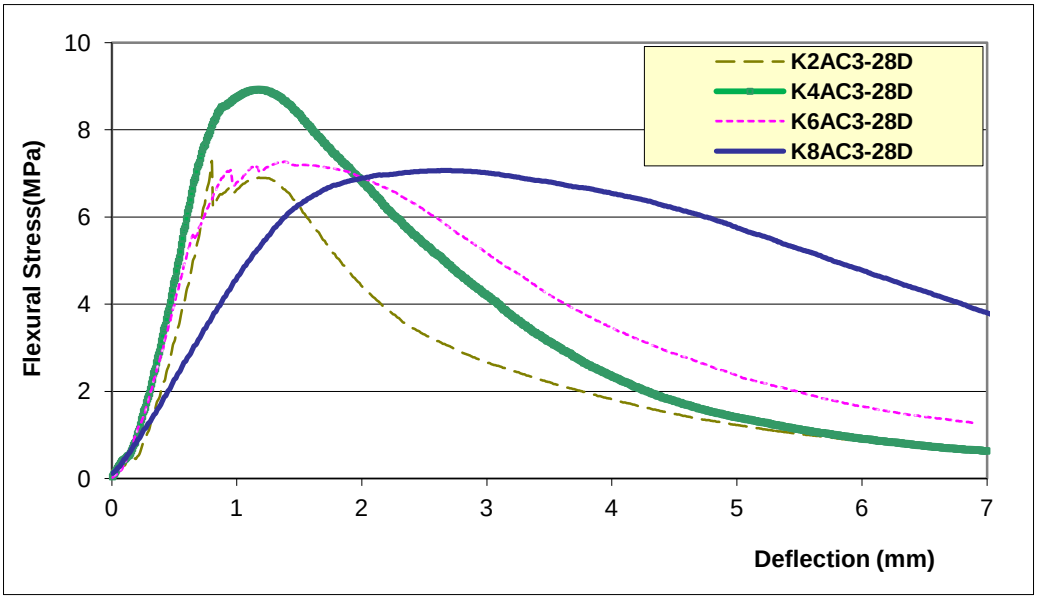

Figure 5-33 Flexural behaviour versus deflection for specimens with 3% acrylic fibres and different amounts of kraft fibres

For a rectangular simple supported beam with a concentrate load at middle, the stress and flexural modulus of elasticity (i.e. initial tangent modulus) are given by (Claisse 2010):

$$E = \frac{l^3}{4bd^3} \times \frac{W}{x} = \frac{\sigma}{x} \times \frac{l^2}{6d}$$

Equation 5-1

Where:

E: flexural modulus of elasticity (or modulus of elasticity in flexure)

W / x: gradient of the load versus deflection

L: length of span

A: cross-section area

b: breadth (width)

d: depth of specimen

σ/x: gradient of the flexural strength versus deflection

Figure 5-30 shows that, by increasing the amount of kraft fibre, a reduction in the Young's modulus of specimens is observed. Approximately this behaviour is observed in figures 5-31 to 5-33.

In order to compare the Young's modulus for all groups, the linear part of stress versus deflection has been selected and, with the above mentioned formula, the flexural modulus of elasticity has been calculated for each specimen. The average of all members in each group has been considered as a representative of each group and they are depicted in figure 5-34. When acrylic fibre content is over 2%, the slope of the elastic part of the stress-deflection relationship curve does not change significantly. Mixes containing 0.5% and 1% acrylic fibre showed the highest elasticity modules.

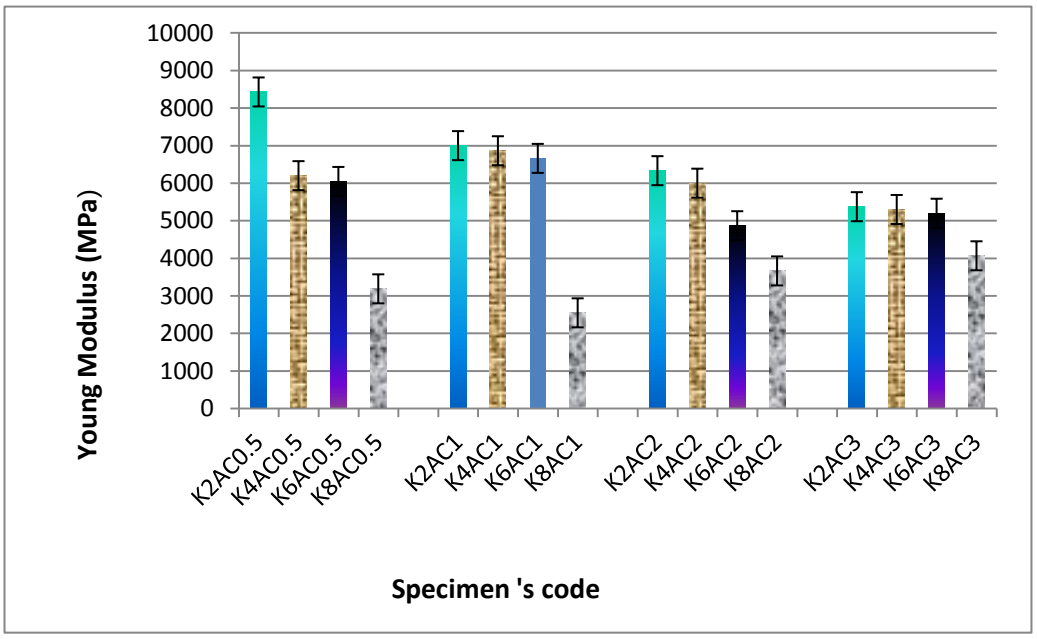

Figure 5-34 Average of flexural modulus of elasticity for specimens reinforced by blending acrylic and kraft fibres

The initial increase in stress leads to hairline cracks developing under the load on the lower surface where maximum tensile strength due to bending momentum occurs. When the cracks open and propagate, if the fibres across the crack have enough bonding with the matrix, they will be pulled out and hence they can provide a crack-bridging force. This force could retard the crack and supply a resistance to the crack opening. As discussed, the interaction features of fibre–cement interfacial areas depend on bonding within the fibres and matrix, and the length and aspect ratio of fibres.

It is clear that there is a close relationship between the flexural strength capacity of the FCB and the crack widths. As the cement matrix can carry just a little bit of tensile strength in the first stage of loading, the initial hairline cracks appear in the middle of specimens where maximum

tensile strength and deflection occur. In specimens with only kraft fibres, crack bridging is provided by kraft fibres' action. When acrylic fibres (with different properties such as longer length, greater aspect ratio and more tensile strength as mentioned in table 3-2) are added to the mixture, an additional bridging action is entered into effect, superimposing the kraft fibres' effect. The combination of bridging action in FCB could change the flexural behaviour.

As already mentioned, the transmission of the force within the fibres and the matrix occurs through the interfacial bonds. Acrylic fibres do not have any fibrils in the lateral surface, any pores or porosity on their surface and they are weak in wettability; consequently, bonding between acrylic fibres and the cement matrix is weaker than for the kraft fibres. On the other hand, acrylic fibres have other important characteristics (given in table 3-2) that are useful in fibre cement. These fibres have lengths longer than the kraft fibres (a kraft fibre length is around 0.9 mm while an acrylic fibre length is about 5mm), high aspect ratio (≈250), higher Young's modulus, higher tensile strength (≈350 MPa), low elongation at break (≈3%), and specific gravity of more than 1 (≈1.18).

However, bonding between acrylic fibres and cement is not as strong as between kraft fibres and cement but their long lengths and small diameters (≈20 micron) lead to a high aspect ratio (≈250) that can compensate for its weakness in bonding so that a little bonding creates between these fibres and hydrated cement paste. The high Young modulus contributes considerably in loading and the low elongation at breaks leads to reduced specimen deflection. Also, the specific gravity of acrylic fibres, which is greater than water (≈ 1.18), helps the fibres to be distributed uniformly in the slurry.

The bond between acrylic fibres and the cement matrix occurs as a result of friction within the matrix and fibres on the interface. Normally, friction occurs as a result of the inter-lock between two surfaces. When two objects have relative motion to each other, an inter-lock will occur on their interface. In FCB, as the strength of the fibres is much higher than that of the cement matrix, when the fibres are pulled out, micro damage occurs in the interface.

The optimum percentage of kraft fibres for use in cement sheets containing both acrylic and kraft fibres depends not only on the amount of kraft fibres but also the amount of acrylic fibres used. In general, according to observations in the figures of section 5.2.2.2, specimens with a low percentage of kraft fibres (less than 4%) blended with 3% acrylic fibres showed better results in flexural strength.

The interface bonding between the matrix and the fibres tends to be weak if an inappropriate proportion of fibre is applied. It causes a non-uniform distribution of fibres or shortage of fibres throughout the matrix. Hence, the pullout force of fibres would decrease. With the decreasing of the pullout force, the flexural strength of the FCB decreases.

The SEM observations for the kraft fibres, acrylic fibres and specimens reinforced by these fibres are illustrated in figures 5-35 to 5-42.

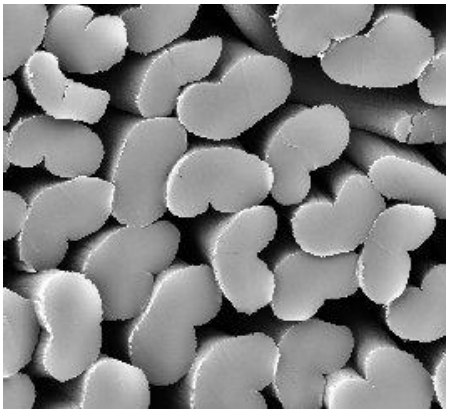

Figure 5-35 SEM image of Cross- sectional kidney shape of acrylic fibres

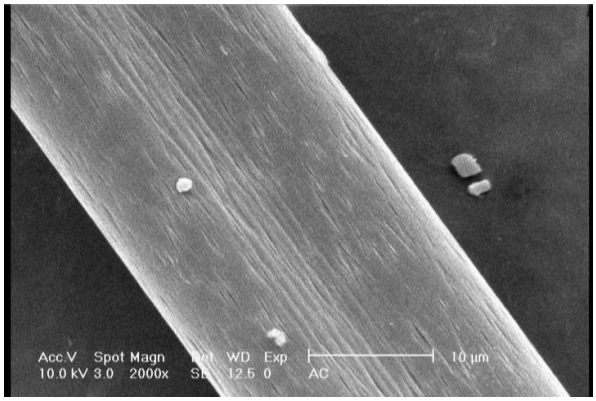

Figure 5-36 SEM image of longitudinal section of acrylic fibres

Figure 5-35 shows the cross-sections of acrylic fibres which are kidney shaped. However, there are no fibrils on their lateral surfaces and their surfaces are a little bit uneven (fig. 5-36). These characteristics cause a little bonding between hydrated cement and these fibres. Figure 5-37 shows a FCB reinforced by both acrylic and kraft fibres. As seen, hydrated cement particles have stuck throughout the kraft fibres and only on some parts of acrylic fibres.

One of the acrylic fibres in figure 5-37 has been magnified in figure 5-38 to be examined in more detail. As observed, as a result of the non-wettability of acrylic fibres, the lateral surfaces of the fibres have not been covered entirely by hydrated cement. Also there are no fibrils around the main fibres to increase bonding with the cement matrix. But the long lengths of these fibres (compared to the kraft fibres) cause them to be tied and relatively surrounded by kraft fibres and hydrated cement particles. In this case, the appropriate characteristics of these fibres, such as tensile strength, modulus of elasticity and elongation at break can enhance the mechanical performance of the composite.

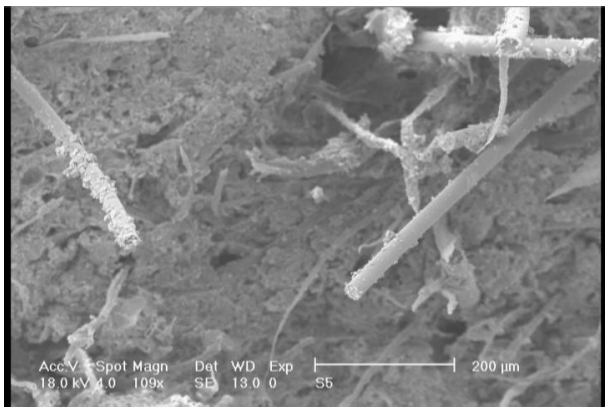

Figure 5-37 SEM image of acrylic and kraft fibres in FCB

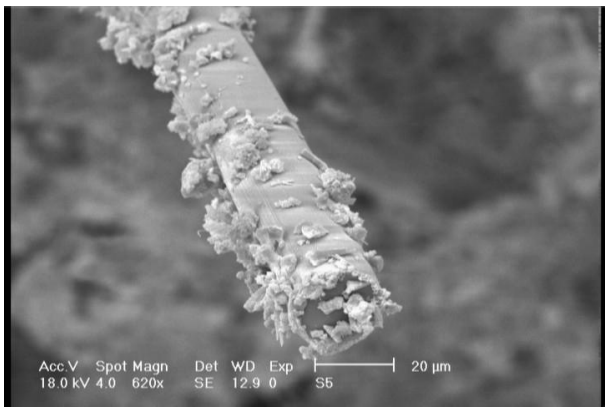

Figure 5-38 SEM image of acrylic- cement bonding

As already mentioned, kraft pulp fibres have a cross- sectional ribbon shape that is shown in figure 5-39. The characteristics of these fibres such as wettability and fibrillation cause a strong bonding of these fibres with hydrated cement particles (fig. 5-40).

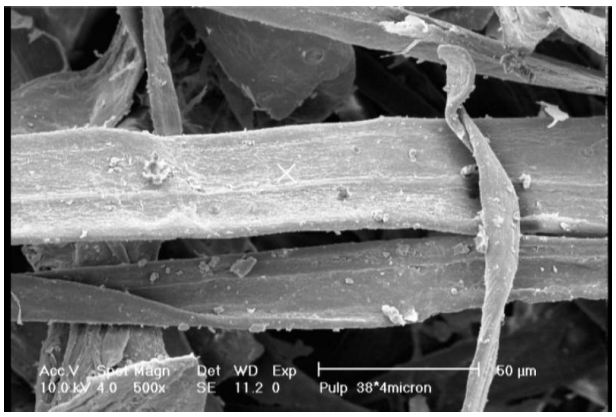

Figure 5-39 kraft pulp fibre with ribbon shape

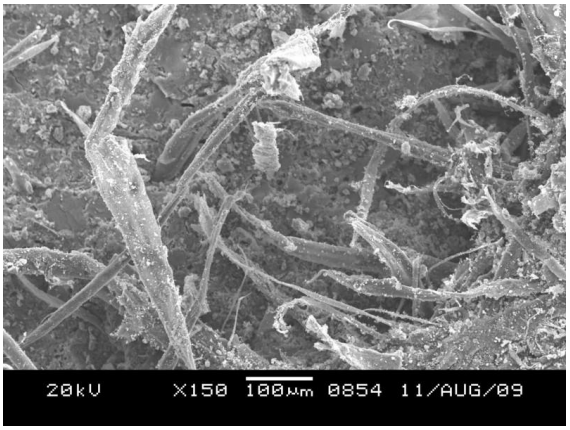

Figure 5-40 Bonding between kraft pulp fibres and hydrated cement particles

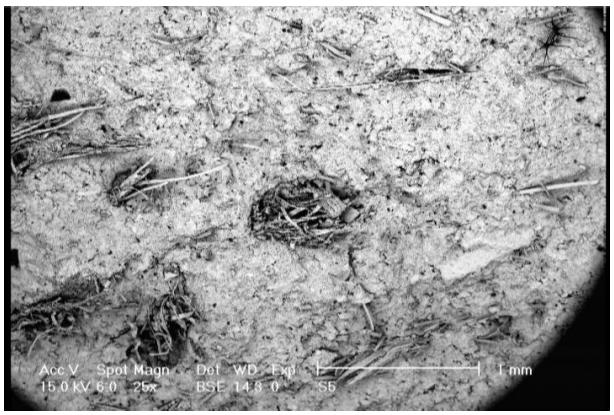

Figure 5-41 Balling (clumping) of fibres in cement matrix

Figure 5-42 Uniform distribution of acrylic and kraft pulp fibres in cement matrix

Increasing fibres more than the optimum amount causes balling (clumping) incidents. As can be seen in figure 5-41, fibres cannot distribute uniformly and they clump together and create some weak points with accumulated fibres. The presence of clumping in the specimens leads to a reduction in the crack-bridging effect to stop cracks due to bending, whereas the initiation of those cracks is made more likely by the greater extension of unreinforced areas found in the specimens.

Figure 5-42 shows a uniform distribution of kraft pulp and acrylic fibres when they are used in their optimum percentage. The high flexural strength of specimens containing optimum fibre content implies that fibres act as crack-bridging and the load is carried by combination of acrylic fibres, kraft pulp fibres and the fibre–cement interface.

5.2.2.3 Effect of limestone powder

This section will deal with the effects of limestone powder (calcium carbonate: $CaCO_3$) in different amounts, i.e. 5%, 10%, 15% and 20%, replacing cement in two separate groups of mixes. The first group is FCB reinforced by 8% kraft solely and the second group is FCB reinforced by 4% kraft and 3% acrylic fibres.

In figure 5-43 the flexural strengths for 7 and 28 days curing of FCB are compared. As observed, as a result of cement hydration the flexural strength increases from 7 to 28 days in all specimens. The error amount for each group is shown in the graphs based on the results of the specimens in each group that was about 5%.

As seen in figure 5-43, the increase of limestone to greater than 10% led to a reduction in flexural strength. This may be due to two different aspects of limestone powder:

- Replacing the cement with limestone powder could lead to a reduction in flexural strength because limestone powder doesn't have cementitious properties. In other words, decreasing the cementitious material in the composite would decrease flexural strength.
- Replacing the cement with limestone powder could lead to an increase in flexural strength because limestone powder particles are much smaller than cement particles and act as fillers to reduce voids.

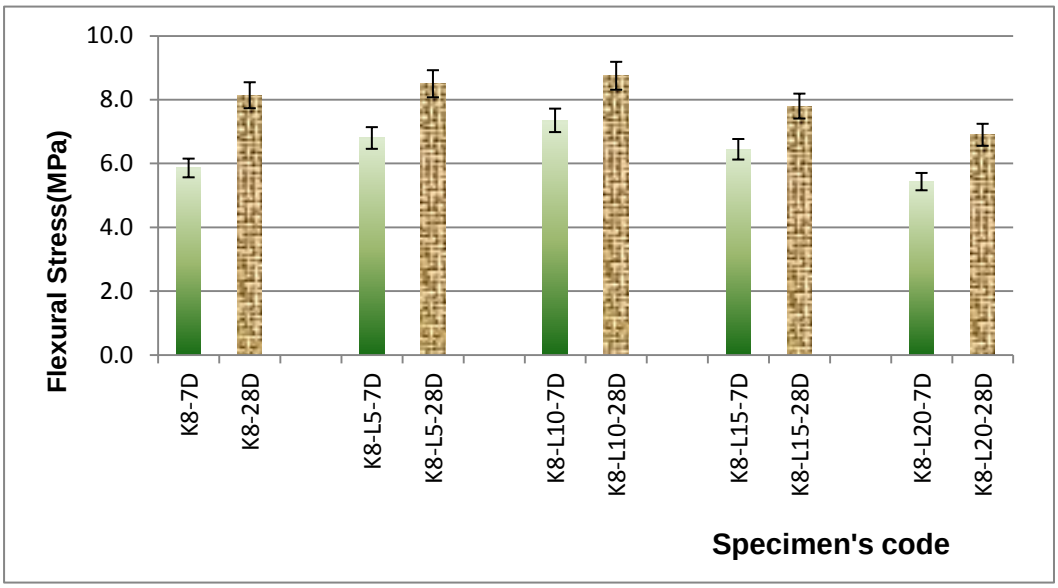

Figure 5-43 The effect of different amounts of limestone powder replacing cement in specimens reinforced solely by 8% kraft pulp

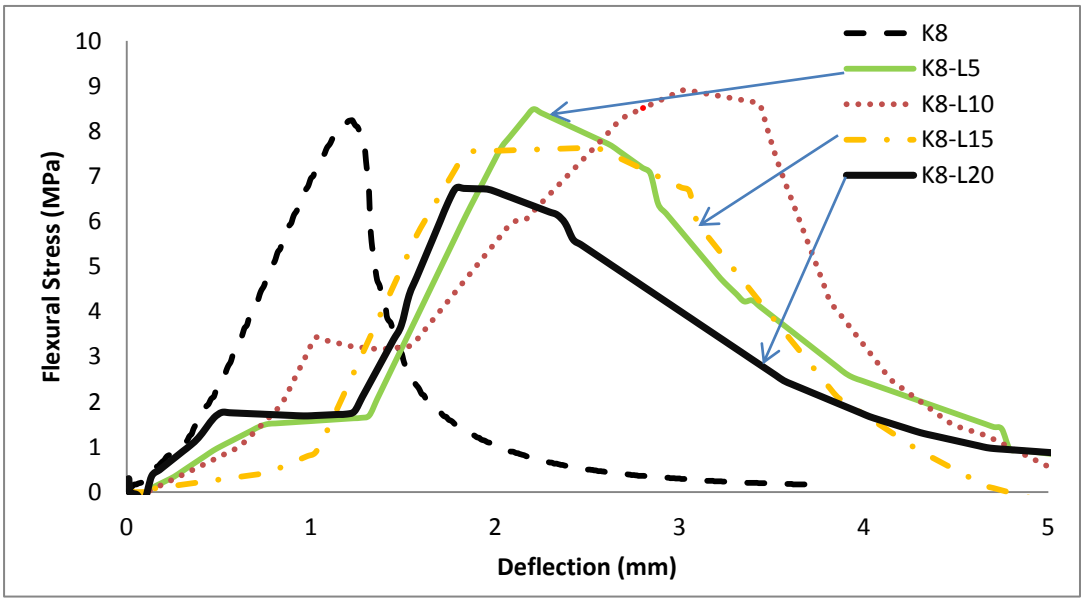

Figure 5-44 Flexural behaviour of FCBs reinforced by 8% kraft and different amounts of limestone powder

Figure 5-44 shows that the specimens containing limestone powder possess a greater ductility. Most of these specimens seem to fail at the same deflection.

The apparent discontinuity in stress development in figure 5-44 and other flexural behaviour graphs where flexural strength is less than about 3MPa is largely due to the settlement of specimens on the jaws. But prompt changes in the gradient of the diagram when the stress is more than 2 MPa may be attributed to the transfer of the load from cement particles to fibres.

Figures 5-43 and 5-44 show that there is no significant difference between maximum flexural strength of K8 and K8-L5, K8-L10.

However, at 10% limestone replacement (Figure 5-44) the specimen fails at a slightly larger flexural stress than other specimens. In addition, this specimen tolerates greater deflection before failing compared to others – approximately 3.5 mm.

The trends in figure 5-44 for the control specimen (no limestone powder) and others are a bit different. Firstly, the peak curves of specimens with 10 and 15% limestone powder are rounded, which suggests a slow fibre pullout failure mechanism, as the composite seems to witness a better residual strain after yielding. Secondly, specimens with a high level of limestone powder (15 and 20%) yield at much lower stress when compared to others. This could be the reason that if too much cementitious material (i.e. cement) is replaced by limestone it causes a weaker bonding within the matrix gradients.

The first slope in the graph might suggest the matrix is taking the stress induced on the composite; it then levels off, suggesting there may be a transition of stress from the matrix to the reinforcement (i.e. fibres). Investigation into the gradients of specimens shows that all

specimens, including the control specimen (i.e. K8), have the approximate identical gradient up to the yielding zone. This means that limestone powder does not have any important effect on the gradient of stress versus deflection. The most important effect of limestone powder is observed in the vicinity of the maximum bearing load of the yielding zone. After failure occurs there is a steep curve, which might suggest that the composite failed, with little residual strain maybe suggesting a combination of fibre snapping and fibre pullout.

As can be seen, once the 10% value (K8-L10) is exceeded, the maximum flexural stress falls down by 10-20% of the corresponding value (K8-L15 and K8-L20), because the limestone largely acts as filler material. When the 10% value is exceeded, the role of filling in voids in the matrix is fulfilled but now the cementitious material is effectively reduced and replaced by the inert limestone powder. This will weaken the matrix fibre interface bonding and results in fibre pullout, yielding a bell-shaped curve, suggesting failure over time.

Figures 5-45 and 5-46 show the results of the flexural tests for specimens reinforced by 4% kraft and 3% acrylic fibres in accordance with different amounts of limestone powder replacing cement.

Comparing these graphs with previous figures (i.e. 5-43 and 5-44) shows that the overall trend of flexural performance of specimens is approximately identical.

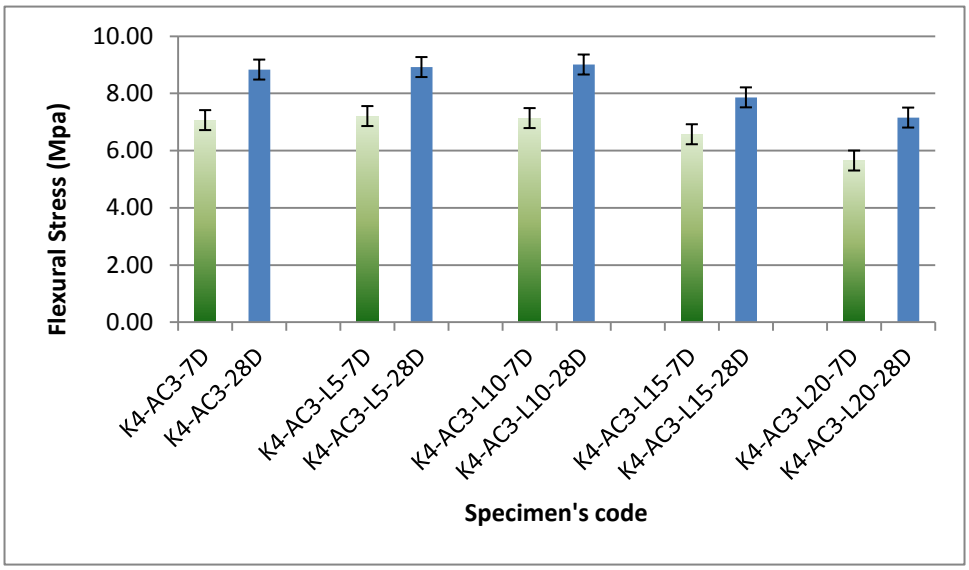

Figure 5-45 The effect of replacing limestone powder for cement in specimens reinforced by 4% kraft pulp and 3% acrylic fibres

As illustrated in figures 5-45 and 5-46, by increasing the amount of limestone powder, the flexural behaviour of specimens is improved up to 10% and replacing more than 10% of the cement with limestone powder led to a reduction in flexural strength and ductility as well.

As can be observed in figure 5-46, replacing cement with 5 and 10% limestone powder does not lead to a significant increase of flexural strength and only has a remarkable effect on improving ductility and area under the curve.

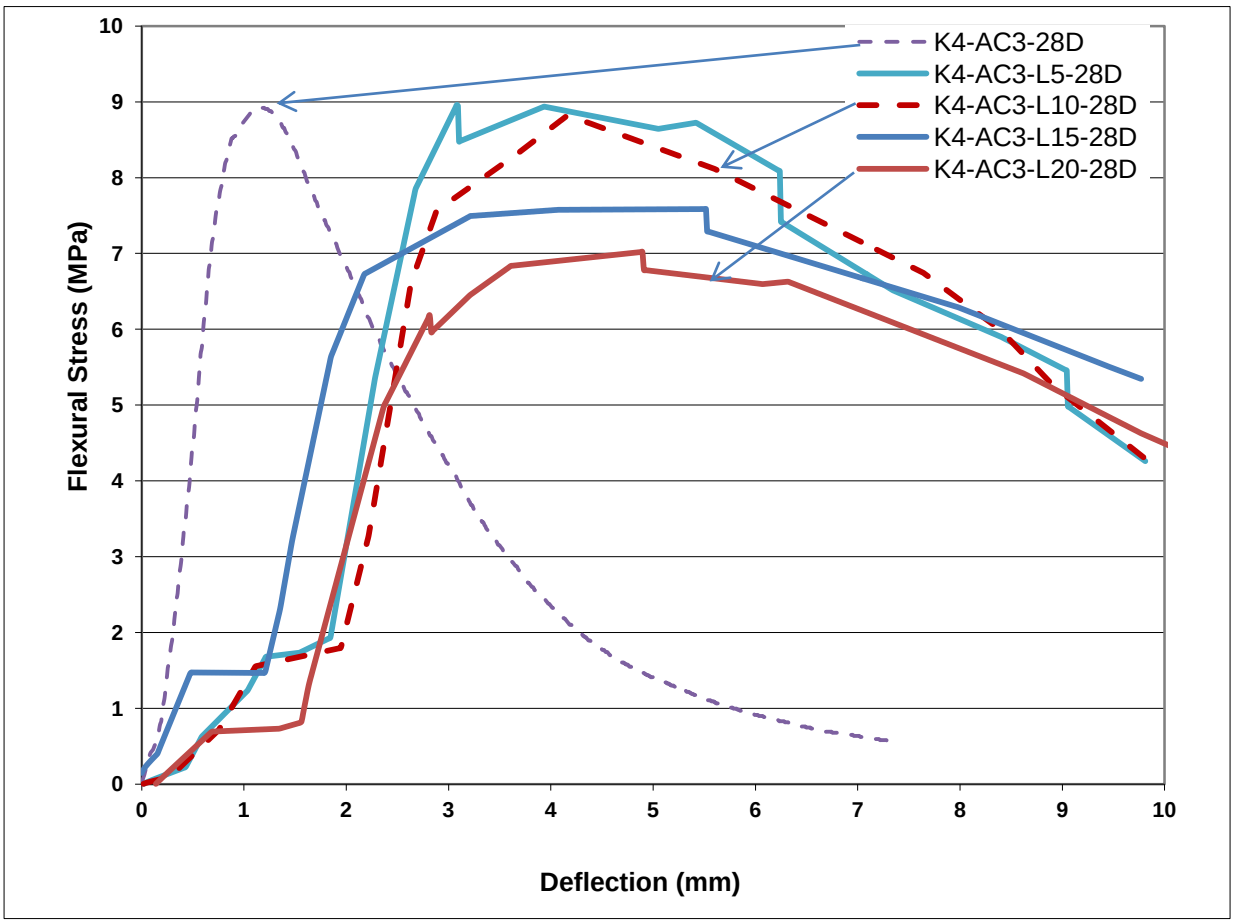

Figure 5-46 Flexural behaviour of FCBs reinforced by 4% kraft and 3% acrylic fibres with different amounts of limestone powder

Therefore, the optimum percentage of limestone powder for specimens reinforced by 3% acrylic and 4%kraft fibres is identical with specimens reinforced solely by 8%kraft and this is 10%.

The most important difference among figures 5-43 to 5-44 and 5-45 to 5-46 is the presence of acrylic fibres that led to the following behaviour:

- As limestone powder does not have any significant effect on acrylic fibres, these results were expected.
- The yielding zone for specimens containing acrylic fibres (figure 5-46) occurs in deflection at 3-7 mm, depending on the amount of limestone powder. But for the specimen without acrylic fibres (figure 5-44), failure occurs in deflection at 2-3.5 mm.
- The area under the graphs in figure 5-46 is more than in figure 5-44. It means the limestone powder has a greater effect on specimens containing both acrylic and kraft fibres in comparison to specimens contain solely Kraft.

It seems that, in specimens containing both acrylic and kraft fibres, limestone powder fills voids in the vicinity of acrylic so that leads to greater toughness.

5.2.2.4 Effects of silica fume

In this section an investigation has been done into the use of silica fume to improve the flexural behaviour of two types of cement board. The first one is cement board reinforced by kraft pulp fibres alone and the second one is cement board reinforced by the blending of kraft and acrylic fibres.

Figures 5-47 and 5-48 indicate the flexural strength of the specimens for both groups. Silica fume was used in different amounts (i.e. 3%, 6%, 9% and 12% replacement of cement by weight) in each group.

As can be observed, 3 and 6% replacement silica fume for the first group causes an insignificant raise in flexural strength and more than 6% led to a reduction in flexural strength in comparison to the control specimen (K8-14D).

In the second group, flexural strength increases when increasing the amount of silica fume from 3% to 9% then it reduces.

Therefore, the highest flexural strength in the first group is obtained when 6% of silica fume are used and this for the second group would be 9%.

Comparing the flexural strength of 7- and 28-day specimens (figures 5-47 and 5-48) shows that, in both groups, flexural strength increases during the curing time.

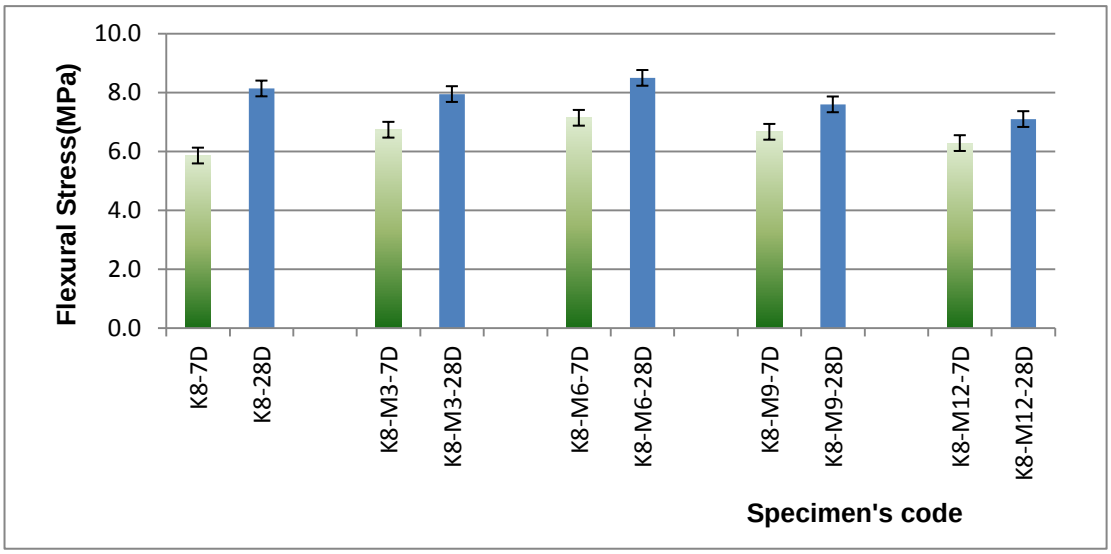

Figure 5-47 The effect of replacing silica for cement in specimens reinforced by 8%kraft pulp fibres

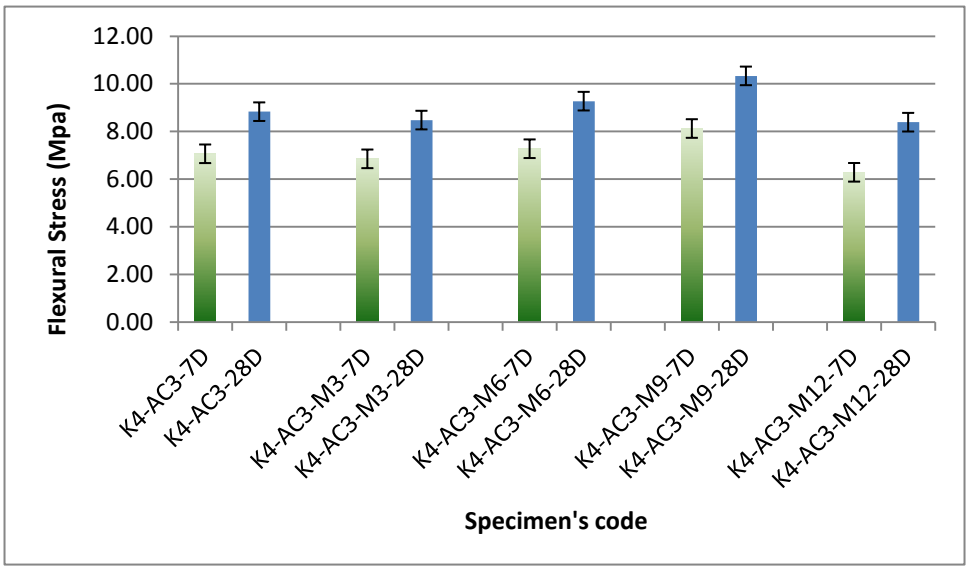

Figure 5-48 The effect of replacing silica fume for cement in specimens reinforced by 4%kraft pulp and 3% acrylic fibres

Silica fume consists largely of amorphous (non-crystalline) silicon dioxide (SiO2), with ultrafine particles. As a result of its large surface area and high SiO2 content, silica fume is categorized as a highly reactive pozzolanic material with a high specific surface, which makes it very suitable as a cementitious material**.**

The pozzolanic reaction of silica fume is associated with an increase in the flexural strength because this ultrafine material has some effects on mixtures.

Improvement in performance of cement board containing silica fume has been proved by some researchers (Chung 2002; Delvasto et al. 2010; de Gutiérrez et al. 2005). They observed that silica fume decreases the capillary action and permeability due to the densification of the composite. For example, Delvasto et al. (2010) showed that the coefficient of capillary absorption is reduced

from 0.0249 to 0.0137 kg/m^2 s$^{1/2}$ and the permeability decreases when silica fume is used in cement board reinforced by fique fibres, which is are a type of Columbian natural fibre.

In addition to the densification of the composite, silica fume has two other effects: 1) replacing silica fume for cement could decrease the alkaline environment of the media (Gutiérrez et al. 2005); and 2) using silica fume in cement board improves fibre dispersion (Chung 2002) throughout the matrix. As already mentioned, kraft cellulose fibres have a little lignin (less than 10%) which can be attacked by alkaline cement; hence this may lead to degradation of some fibres resulting in a reduction in the strength of the composite. Also, high alkaline media could reduce the mechanical properties of acrylic fibres.

Also, silica fume can act as a filler material within the cement matrix, which leads to a reduction in the porosity of the composite as voids containing air and moisture are filled.

It seems the pozzolanic reaction of silica fume causes the formation of hydrated calcium silicate, which aids in giving higher strength.

Figures 5-49 and 5-50 compare the flexural behaviour of specimens in both groups. Figure 5-49 shows that all specimens containing silica fume have more area under the curve in comparison to the control specimens (i.e. K8-14D). However, the trend of flexural behaviour in the different steps of loading is a little bit different to the control specimen.

The gradients of diagrams after the maximum strength (peak point) are less than for the control specimens. In other words, the rate of losing load bearing capacity for the specimens reinforced by silica fume is better than for the control specimen.

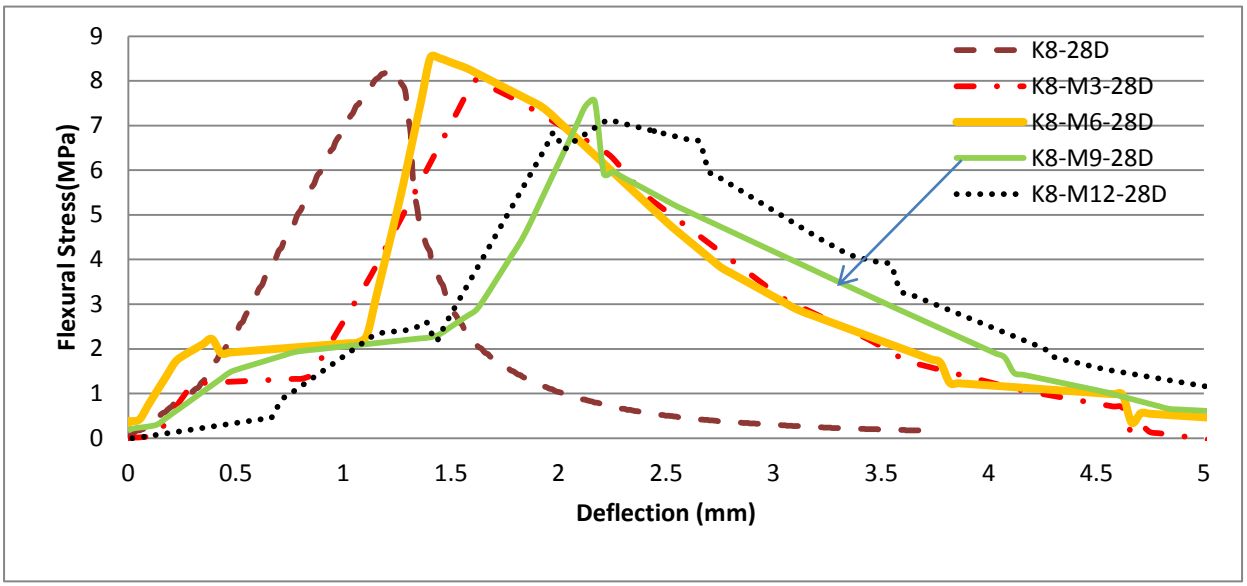

Figure 5-49 Flexural behaviour of FCBs reinforced by 8% kraft pulp fibres and different amounts of silica fume

Figure 5-50 shows the flexural behaviour of specimens reinforced by blending acrylic and kraft fibres in conjunction with different amounts of silica fume. As can be observed, the role of silica fume in increasing area under the curve for these specimens is considerable. The best behaviour is associated with K4-AC3-M9, which contains 9% silica fume. As seen in figure 5-50, 3% and 12% replacement of cement for silica fume causes an increase in ductility but reduces flexural strength. This behaviour shows that, in spite of figure 5-49, which showed 3 and 6% replacement of cement by silica fume were the best substitutions, in figure 5-50, the best substitutions are 6% and 9%. The most important reason for this is the presence of acrylic in specimens, which could change the optimum value of silica fume.

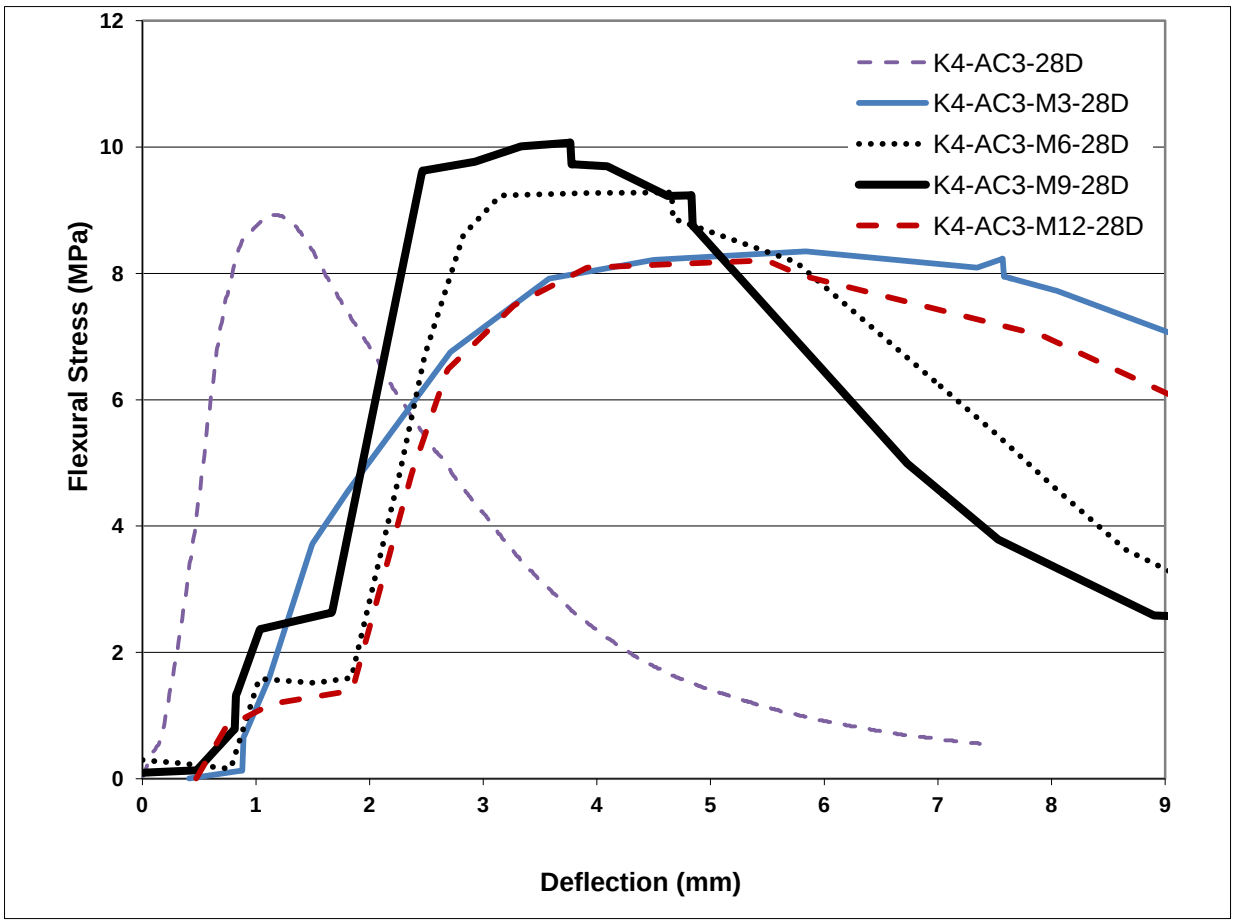

Figure 5-50 Flexural behaviour of FCBs reinforced by 4% kraft and 3% acrylic fibres with different amounts of silica fume

5.2.2.6 Effects of combination of silica fume and limestone powder

The effects of limestone powder and silica fume were investigated in previous sections separately (i.e. 5.2.2.4 and 5.2.2.5). The results showed that 10% limestone powder was the suitable percentage of materials which act only as fillers in both groups, specimens reinforced by kraft alone and specimens reinforced by blending kraft and acrylic fibres.

In this section, the effect of the combination of limestone powder and silica fume is investigated. As already mentioned, 10% limestone powder was chosen as a reference percentage of limestone in conjunction with different amounts (3%, 6% and 9%) of silica fume.

As can be seen in figures 5-51 and 5-52 in specimens containing kraft fibres alone (in the absence of acrylic fibres), the highest flexural strength and the best flexural behaviour is associated with specimens reinforced by 10% limestone powder and 3% silica fume.

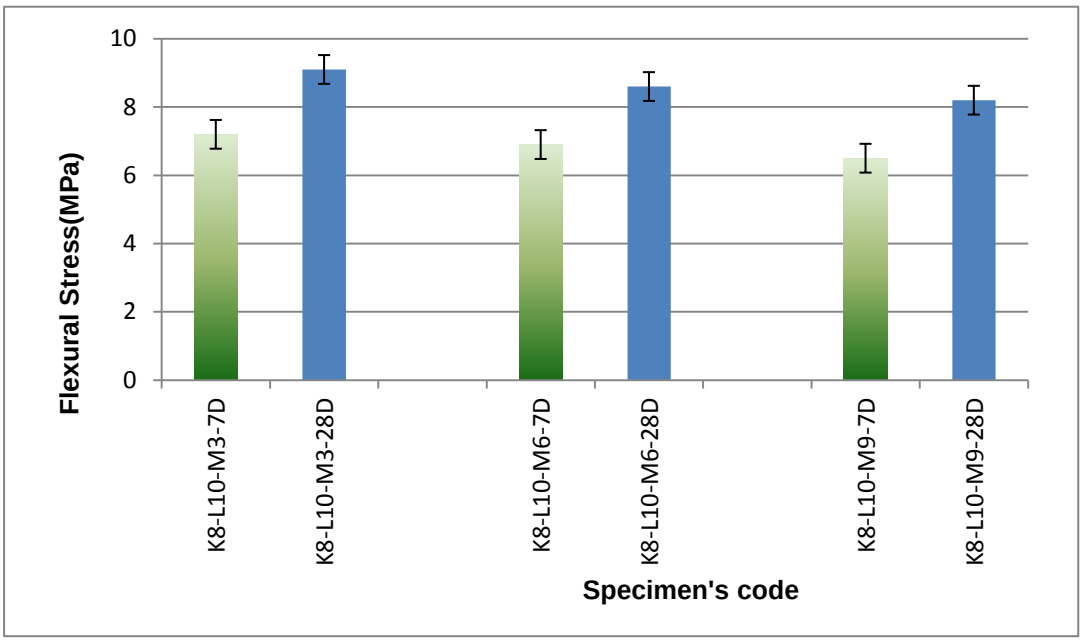

Figure 5-51 The effect of replacing 10% limestone powder and different percentages (3, 6 and 9%) of silica fume for cement in specimens reinforced by 8% kraft fibre

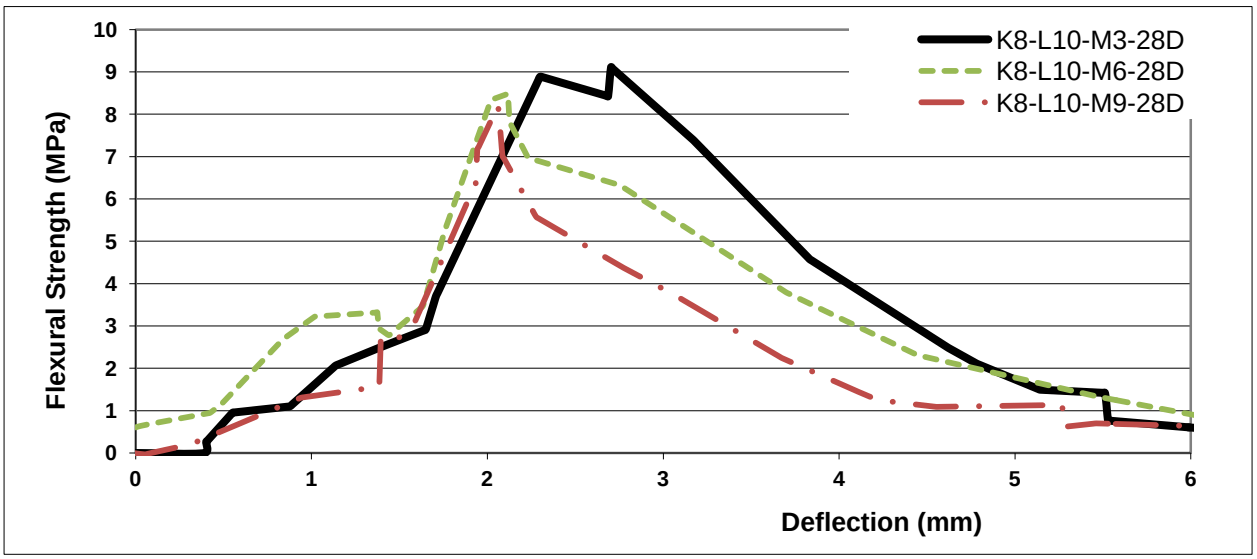

Figure 5-52 Flexural behaviour of FCBs reinforced by 8% kraft fibres in conjunction with 10% limestone powder and different amounts (3,6 and 9%) of silica fume

It seems that the specimens could be improved if replacement ratio of silica fume 3% is used when the amount of limestone powder is 10%. These replacements can compensate for the missing cement.

However, the reduction in flexural strength and area under the curve for the other two specimens of this group is not considerable (figure 5-52).

As observed, K8-L10-M3 has the highest flexural strength. This group also shows the better crack bridging at the peak point while it is experiencing a yielding zone.

It seems that a combination of limestone powder and silica fume in conjunction with cement could change the optimum value for these materials in comparison with those conditions that each one is used separately.

This may be due to better distribution of their particles with different sizes in conjunction with hydrated cement products.

Figure 5- 53 shows flexural strength in the second group containing 4% kraft and 3% acrylic fibres in conjunction with 10% limestone powder and different amounts of silica fume. Three important points are observable in this figure:

- For the group with 3% silica fume replacing 3% cement and 10% limestone powder replacing 10% cement, flexural strength would be 10.3 MPa which is related to K4-AC3-L10-M3. This is the highest flexural strength obtained in laboratory tests in this research.
- For all specimens of this group, by increasing the age of specimens from 7 to 28 days, flexural strength increases.
- By increasing the amount of silica fume (more than 3%), flexural strength decreases with a regular trend for both 7- and 28-day specimens.

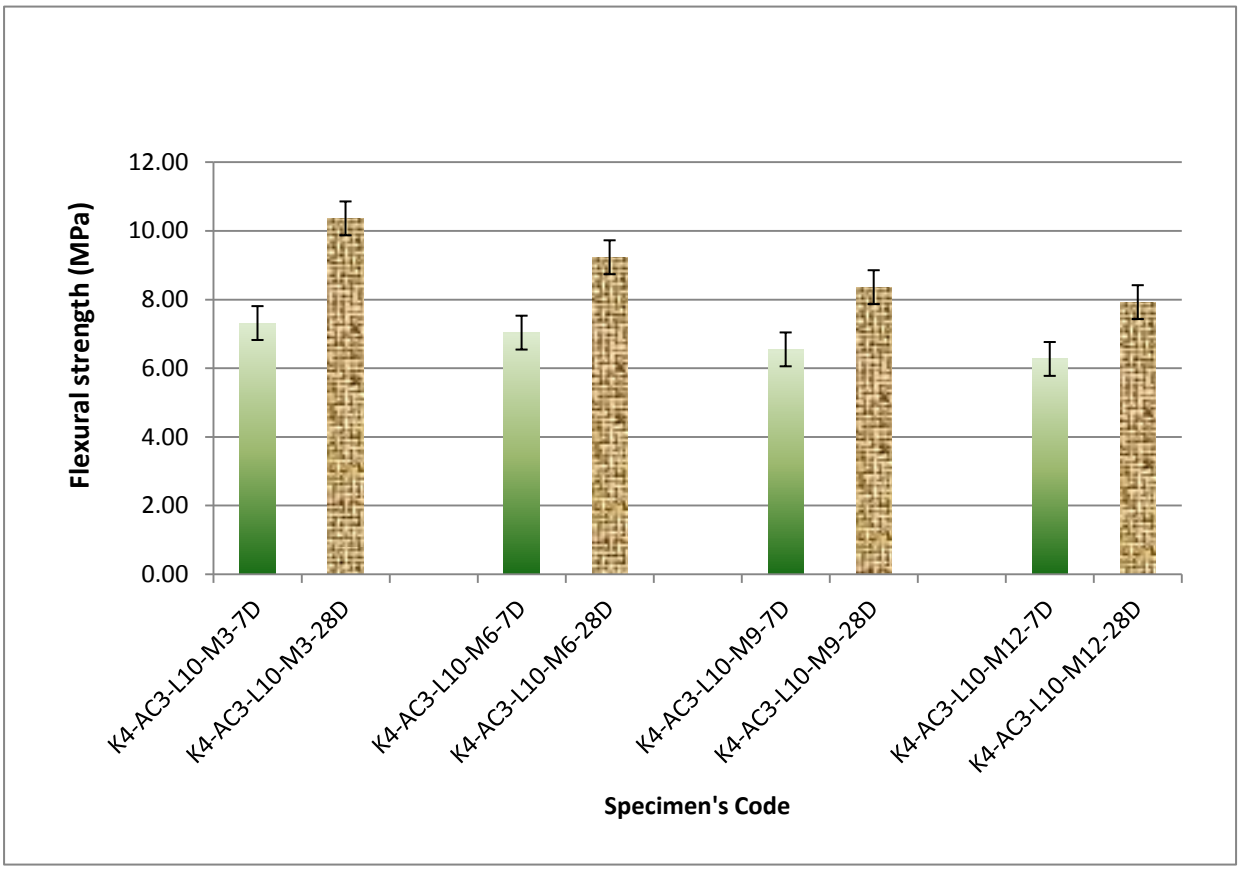

Figure 5-53 Flexural behaviour of FCBs reinforced by 8% kraft fibres in conjunction with 10% limestone powder and different amounts (3,6 and 9%) of silica fume

As illustrated in figure 5-53, the combination of limestone powder and silica fume may obtain higher flexural strength but the study of the flexural performance of those groups is important as well.

Therefore, the flexural performances of the final mixes for the 7-day and 28-day specimens are shown in figures 5-54 and 5-55.

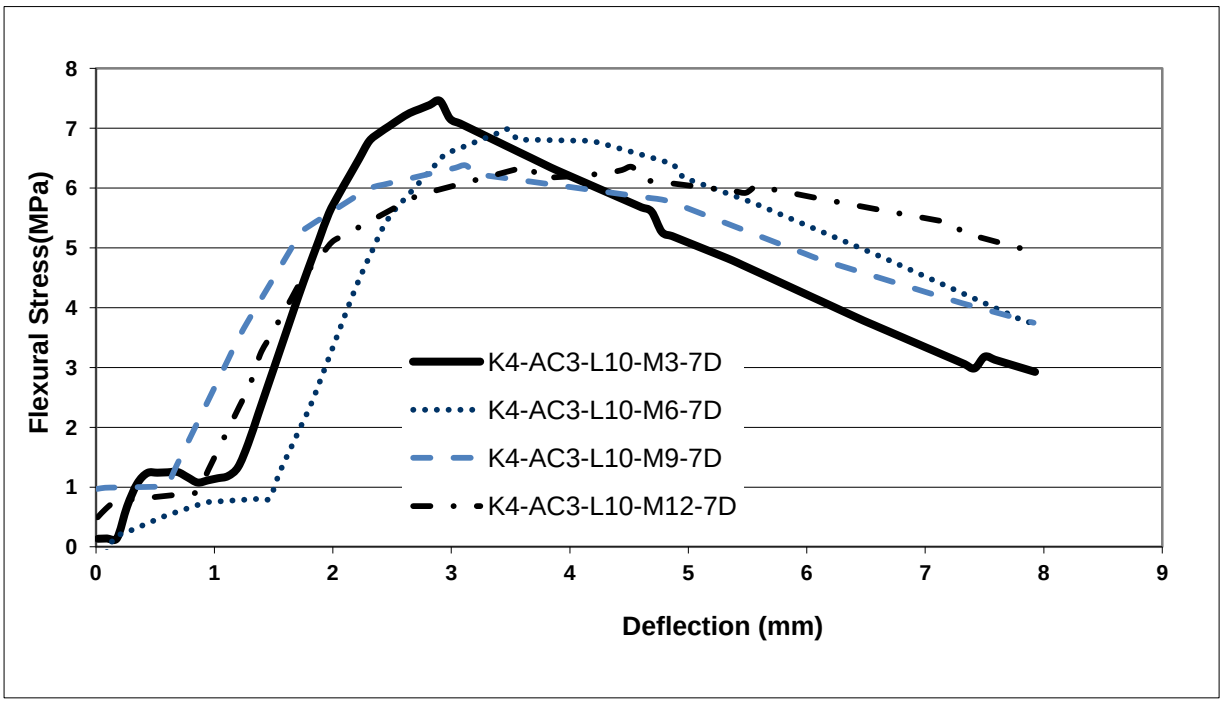

Figure 5-54 The 7-day flexural behaviour of FCBs reinforced by 4% kraft and 3% acrylic fibres in conjunction with 10% limestone powder and different amounts (3,6,9 and 12%) of silica fume

Comparing the flexural behaviour of the 7- and 28-day specimens shows that both the area under the curve and the flexural strength of specimens increased during the curing time. It means there is an appropriate consistency within acrylic fibres, kraft pulp fibres and cementitious materials.

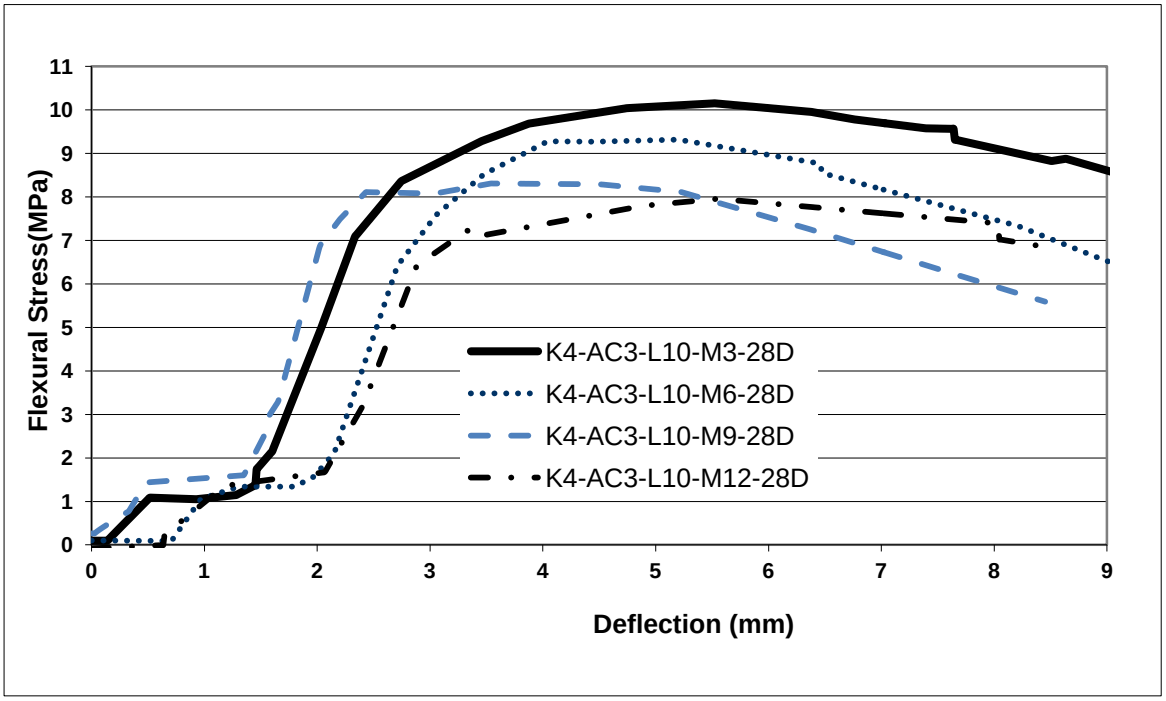

Figure 5-55 The 28-day flexural behaviour of FCBs reinforced by 4% kraft and 3% acrylic fibres in conjunction with 10% limestone powder and different amounts (3,6,9 and 12%) of silica fume

Silica fume is very fine noncrystalline silica with particles having diameters up to 100 times smaller than Portland cement and a high pozzolanic reaction (Chung 2002). The presence of limestone powder with a small particle size in the vicinity of cement particles and silica fume can lead to a decrease in flaws and cracks in the matrix–fibre interface.

This was confirmed in the laboratory so that the filtration time by vacuum pump increased when a combination of limestone powder and silica fume was used in the cement board.

Figure 5-56 shows a schematic concentration of composite ingredients in the vicinity of fibres, particularly acrylic fibres that have less wettability.

Figure 5-56 The schematic effect of a combination of limestone powder and silica fume in the fibre-matrix interface

It seems that the combination of both silica fume and limestone powder in the matrix not only leads to an increase in the fibre reinforcement effect, but also helps the fibre dispersion. This idea can be attested by observation of manufactured specimens' appearance in that the accumulation of fibres on the top surface of specimens is more homogeneous and uniform.

5.3 Physical tests

Generally, physical tests are carried out by providing important information regarding the physical properties of the cement boards under examination. The most common tests are density, moisture movement, water absorption and moisture content.

These tests are designed to assess the capabilities of cement board in different ambient conditions. Most of the relevant international standards such as BS EN 494 and ASTM c1185 don't specify particular values for physical properties of cement boards and are just concentrated on the method of testing. This may be due to different application of cement boards and different ambient conditions in each country. For this reason, each cement board factory usually specifies some of the physical properties of the products in its brochure. As this research was concentrated on replacing asbestos fibres on Iranian asbestos-cement boards, the Iranian specification for asbestos- cement board number 575 is referred to, at the end of each corresponding section as rough criteria.

For example, Iranian national specification No. 575 declares that density of cement board is 1.6 ± 0.1 gr/cm^3. And BS EN 12467 just pointed that the apparent density shall be greater than 1.00 gr/cm^3.

As the most important tests for factories are mechanical tests, so those tests were in the first priority and were conducted for all primary, secondary and final mixes. Then as the highest flexural strength belonged to the final mixes so the physical tests were just done for that group to identify the physical properties of that group.

5.3.1 Density

Figure 5-57 shows the effect of increasing replacement ratio of silica fume and limestone powder for cement in specimens reinforced by kraft fibres. In addition, the effect of the combination of limestone powder and silica fume is demonstrated in the last three columns of this chart.

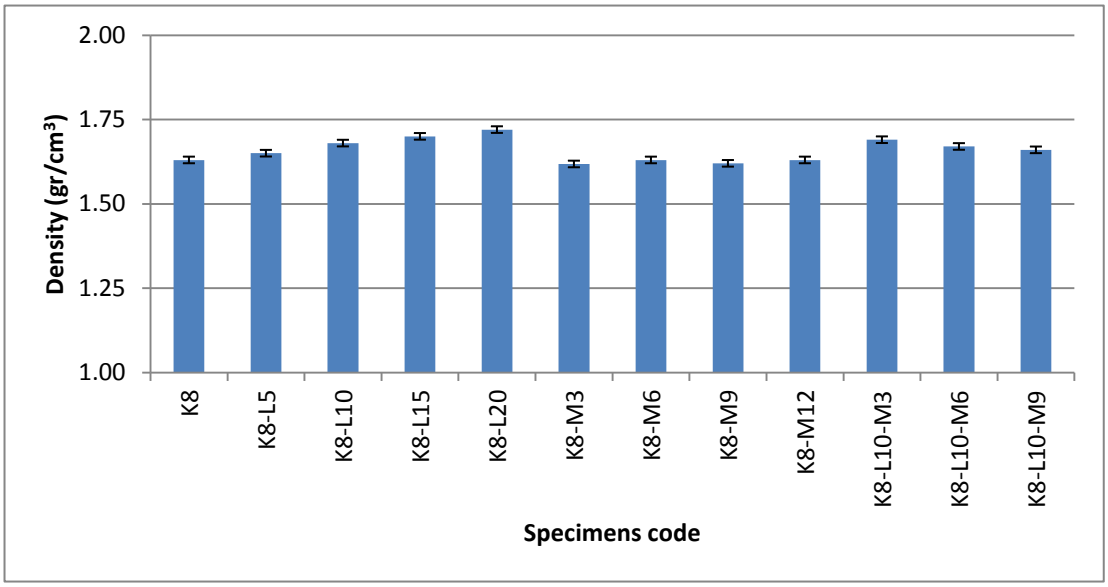

Figure 5-57 Density of FCB reinforced by kraft fibres in conjunction with silica fume and limestone powder

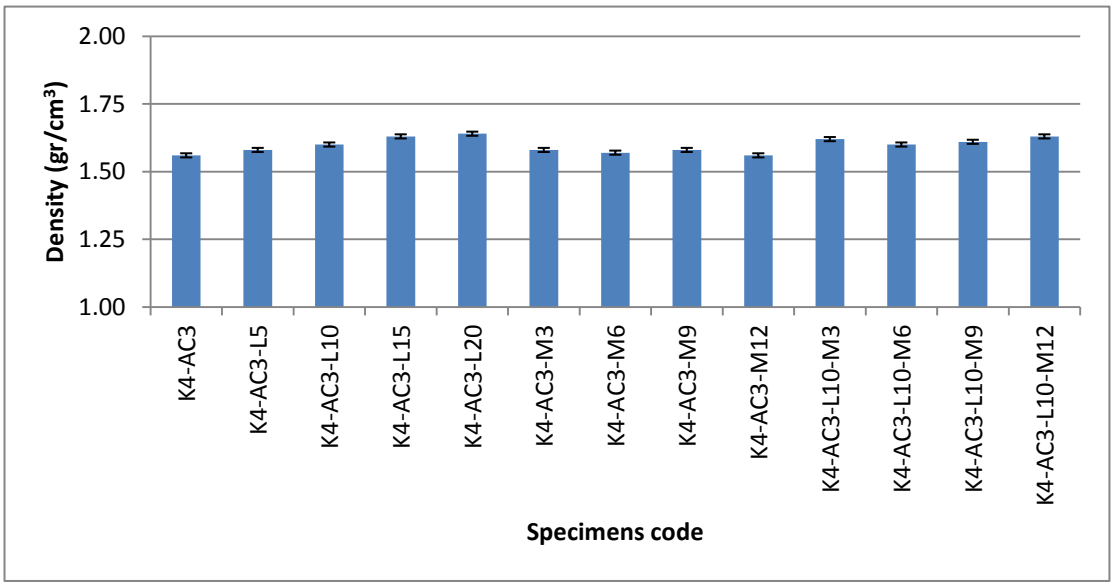

Figure 5-58 Density of FCB reinforced by kraft and acrylic fibres in conjunction with silica fume and limestone powder

Figure 5-58 compares the density of specimens made out of different replacement ratios of silica fume and limestone powder in conjunction with acrylic and kraft fibres. The combination effect of silica fume and limestone powder is also observed in this chart.

As Figures 5-57 and 5-58 show, no significant changes in density are observed in any of the mixes. This means the presence of fibres and additives cannot change the density of the composite dramatically. However, changes in density for some mixes, such as K8, K8-L20, K8-L10-M3and K4-AC3, are more than other groups.

The reason for these changes in density for those aforementioned groups can be attributed to several parameters, such as the density of additives, the effect of the inclusion of fibres in the matrix and the cement hydration products.

It should be noted that limestone powder (calcium carbonate), which has a density of 2.7 gr/cm^3, does not have any important reaction with hydrated cement products. As limestone powder replaces cement, its density influences the specimen's density because the density of hydrated cement is approximately 2.15 gr/cm^3 while the density of limestone powder, which does not participate in the reactions, is relatively greater than hydrated cement. Therefore it is expected that, by increasing the limestone powder, the density of specimens increases. This prediction can be observed in both figures 5-57 and 5-58.

Another important point is the size of silica fume and limestone powder particles. As a result of the small particle sizes of limestone powder and silica fume (both are less than 25 micron while cement particle size is less than 75 micron), voids within the cement matrix can be filled by these fine particles.

The density of specimens containing solely silica fume is close to that of the control specimen. This may be due to the fact that silica fume has pozzolanic activity and its specific gravity is 2.35 but, when it reacts with cement products, the density of the final outcome products is similar to that of normal hydrated cement products. So, no significant effect of silica fume is observed in the density of specimens containing silica fume.

At the end of this section it is worth paying attention to figures 5-57 and 5-58, which show the apparent highest densities belong to K8-L20 and K4-AC3-L20, but the strongest specimen in flexural strength is K8-L10-M3 (figure 5-51) and K4-AC3-L10-M3 (figure 5-53). This shows that specimens with the highest flexural strength are not necessarily the densest. In other words, the types of fibre and fibre content, bonding in the fibre–cement interface and additives have

complex interactions on each other, which make difficult to find a simple relationship between density and flexural strength.

5.3.2 Moisture movement

The results of the average moisture movement for each mix type are shown in figures 5-59 and 5-58. As a result of limitations to the precision of the measuring equipment of 0.01 mm, the results of moisture movement are presented within the range of 0, 0.05 and 0.1%. In these figures, the measured moisture movement for some specimens is 0.

As can be seen from figures 5-59 and 5-60, all specimens' expansion in length due to moisture movement is equal or less than 0.1%. In other words, the results are insignificant and extremely small values.

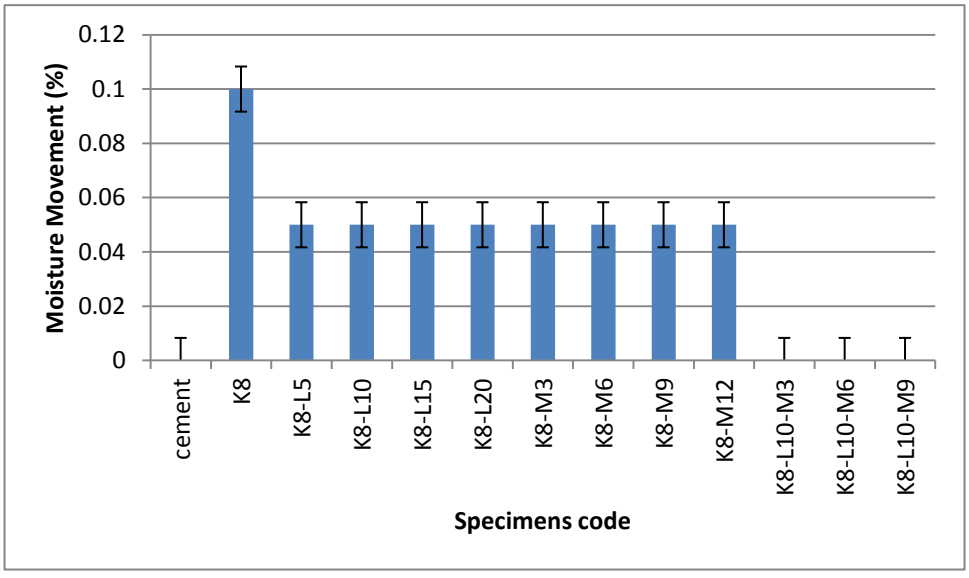

Figure 5-59 Moisture movement of FCB reinforced by kraft fibres in conjunction with silica fume and limestone powder

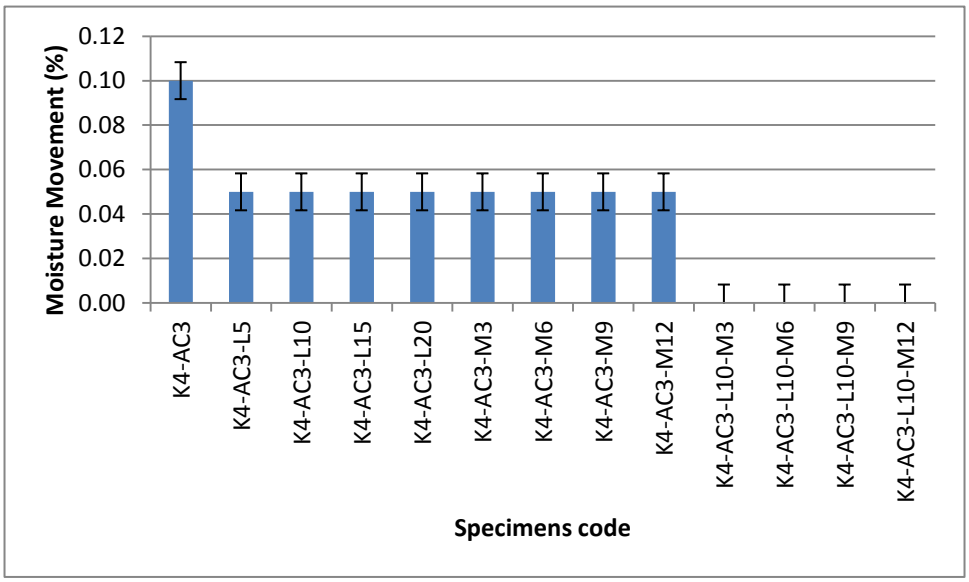

Figure 5-60 Moisture movement of FCB reinforced by kraft and acrylic fibres in conjunction with silica fume and limestone powder

According to the test results in figures 5-59 and 5-60, specimens containing solely fibres (without silica fume and/or limestone powder) show the highest value of 0.1% in moisture, which is still insignificant.

The following discussion may describe the behaviour of fibres, silica fume and limestone powder when they are subjected to the moisture movement test.

- As a result of their moisture-absorbing property, which is one of the most important characteristics of natural fibres, the volume of kraft fibres increases. This leads to an elongation of the length of specimens. Brouwer (2000) measured many characteristics of natural fibres, including moisture absorption. He showed that, depending on the type of fibre, they may absorb moisture between 7 and 25%.

- Using limestone powder as filler in the specimens leads to a confinement of fibres, thereby restraining the fibres from swelling and thus reducing the moisture movement of whole specimen.
- The behaviours of specimens in figures 5-59 and 5-60 are very similar to each other. In both figures, the moisture movement for control specimens (specimens without silica fume and/or limestone powder) were measured as 0.1%. It shows that, as the fibre content for K8 and K4-AC3 is approximately the same (7-8%), the moisture movement for both is identical. It seems, as the percentage of fibres (kraft and/or acrylic) increases the moisture movement also increases; this is due to increased porosity either in creation of larger voids within the specimen or the form of small capillaries in fibres. Both can absorb moisture by a capillary action that can lead to an increase in the length of the specimen. Porosity will be discussed in more detail in section 5.3.3.
- It seems there is a difference between the role of acrylic fibres and kraft fibres in moisture movement. Acrylic fibres do not have hydrophilic properties like kraft fibres. kraft fibres are highly hydrophilic and can absorb water and they bond very well with hydrated cementitious materials. Therefore, the increasing moisture movement in specimens with a high content of kraft fibres is largely due to the hydrophilic properties of kraft fibres. Acrylic fibres have hydrophobic properties so an increase in the moisture movement of specimens containing acrylic fibres could be related to an increase of pores and voids in specimens, particularly in the fibre–cement interface because its wettability is weak and no strong bonding occurs between fibres and hydrated cement. For this

reason, using very fine cementitious materials such as silica fume can fill voids, limiting kraft fibres' freedom to swell and thus reducing moisture movement.

Therefore, as stated previously and based on the results in figures 5-59 and 5-60, the most important role of silica fume and limestone powder is to fill the voids within either kraft fibres or whole composites and hence reduce the amount of space for water to be absorbed and also limit the amount of water that can penetrate the specimen.

At the end of this section, it should be noted that Iranian national specification No. 575 declares that moisture movement of cement board should be less than 0.1%.

5.3.3 Water absorption

Figures 5-61 and 5-62 show the results of water absorption for both groups of specimens, with and without acrylic fibres, as specified in section 4.4.2.3. Water absorption of fibre cement board is one of the main features that can be important for durability.

As can be seen, the water absorption of the reference specimen (cement in figure 5-61) has one the lowest water absorptions (13%) and, as fibre content increases, water absorption also increases to a maximum of 17%.

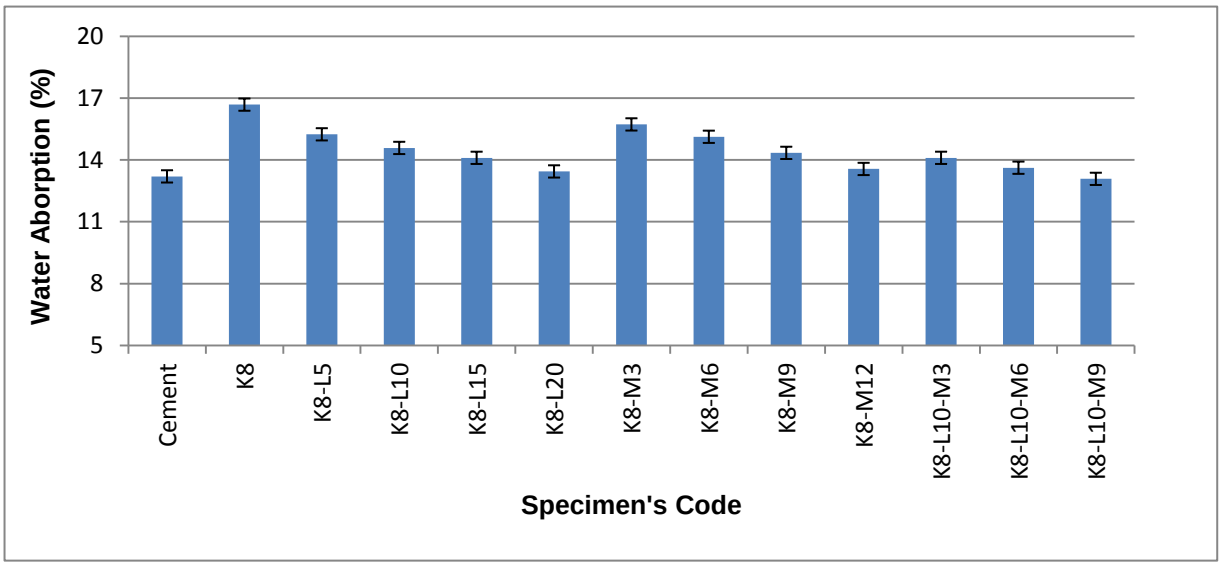

Figure 5-61 Water absorption of FCB reinforced by kraft fibres in conjunction with silica fume and limestone powder

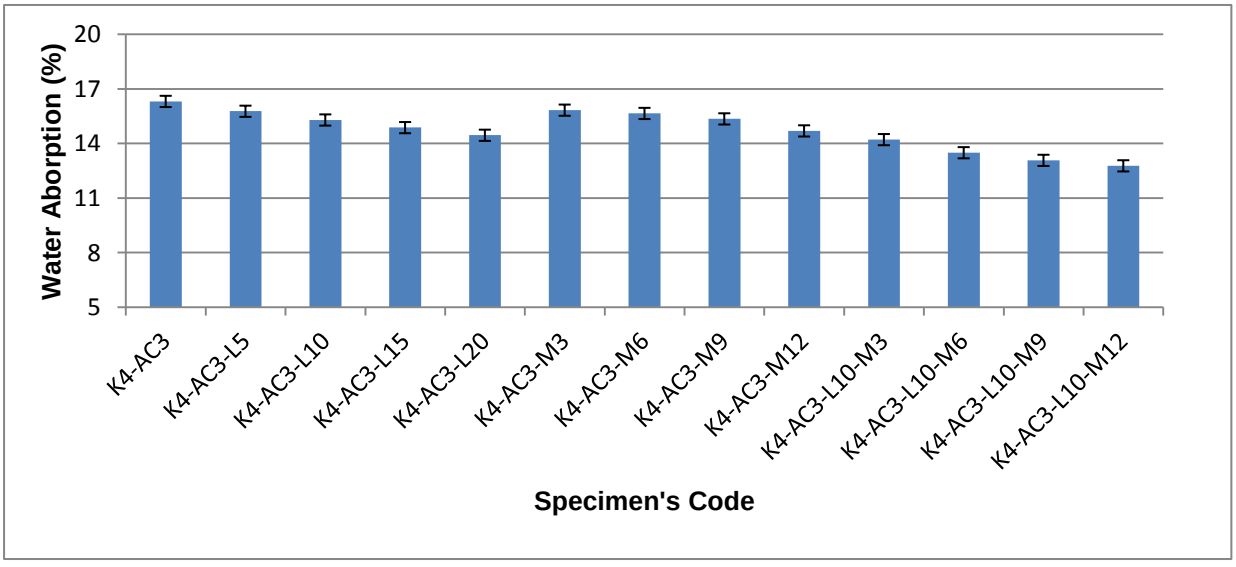

Figure 5-62 Water absorption of FCB reinforced by kraft and acrylic fibres in conjunction with silica fume and limestone powder

The introduction of limestone powder and/or silica fume causes a reduction in water absorption to 13%, which is identical to the reference specimen. The range of variation in figure 5-61 is higher than in figure 5-62. It means that the inclusion of acrylic fibres in the specimen containing kraft fibres can reduce its sensitivity to water absorption. The mechanism of water absorption in fibre cement board can be discussed as follows:

- When limestone powder is increased from 0 to 20% in 5% intervals the water absorption decreases to 13.5% and a similar reduction is also recorded when silica fume is used. The addition of acrylic or kraft fibres obviously increases the amount of voids within the matrix, resulting in water being forced into the matrix due to the water pressure acting on specimens when they are submerged. This will be investigated in the next pages from the viewpoint of porosity.
- One of the most important differences between the water absorption test and the moisture movement test is related to the mechanism of void function. Larger voids can allow water to enter the specimen through the water pressure, rather than through smaller capillaries which are important in moisture movement. In other words, capillary action (which is produced by very small and tiny voids) will be more important when the dry specimen is put in high humidity conditions and big voids would be important when the water enters the specimen as a result of water pressure.
- Comparatively, a small increase in water absorption is observed (figure 5-62 compared to figure 5-61) when acrylic fibres are introduced into the matrix. This could be due to the fact that acrylic fibre is a hydrophobic material that doesn’t have wettability properties.

For this reason it increases the porosity of the composite, thus an increase in water absorption is observed.

- Greater increases in the percentage addition of silica fume or limestone powder could lead to further reductions in water absorption, which could be useful in some applications, even though it would have further costs. This confirms statements already made that mixes containing silica fume and limestone powder normally have lower water absorption than specimens without those additives because the voids are filled by fine particles.
- As observed in both figures 5-61 and 5-62, in most cases inclusion of both limestone powder and silica fume reduces the water absorption of specimens rather than using each one separately. This is most likely due to the better particle grading and chemical reaction of silica fume in the matrix. It is expected that, if the amount of silica fume and limestone increase at higher volumes, further reductions in water absorption may be seen.
- Increasing the fibre content in the cement matrix can increase voids (pores) in the specimen because the vacuum system works with constant power; as the fibre content increases, the pores(voids) in the fibre–matrix interface increase. Thus removing the air within the fibres and the cement matrix would be difficult. As the vacuum pump cannot extract the trapped water within the fibres and the cement matrix, increasing the time or suction power of the vacuum pump may reduce the porosity and then water absorption. Because trapped water could be evaporated over a long period of time and would leave voids in its place. To investigate this, further research need to be done.

- The dimensions of natural fibres change with relative humidity fluctuations (Smook 2002). This is explained by the fact that the equatorial position of the hydroxyls on the cellulose chain causes a lateral polarity along the extended molecule. This positioning makes them readily available for hydrogen bonding. These hydrogen bonds cause the chains to group together in highly ordered (crystal-like) structures. Since the chains are usually longer than the crystalline regions, they are thought to pass through several different crystalline regions, with areas of disorder. The inter-chain hydrogen bonds in the crystalline regions are strong, giving the resultant fibres good strength and insolubility in most solvents. They also prevent cellulose from decomposition in alkaline media. In the less ordered regions, the chains are further apart and more available for hydrogen bonding to other molecules, such as water (Delvasto et al. 2010).

Increased water uptake by composites could be an important drawback of a composite when a cement board experiences cycles of water uptake and release in different weather conditions. Consecutive changing of the volume of fibres (i.e. kraft fibres) due to water absorption within the matrix leads to reduced adhesion at the fibre–matrix interface resulting in the disjointing of the fibres and degradation of the cement board under loading. Also apparent mechanical properties could be affected by the water absorption. Therefore, water-saturated specimens may present poor mechanical properties such as lower values of Young's modulus and stress at maximum load. Water may act as a plasticizer, leading to slightly higher values of strain. Much research needs to be done to identify the effects of water absorption on the mechanical and physical properties of FCB.

It should be noted that according to Iranian national specification No. 575 water absorption of cement board should be less than 20%.

5.3.3.1 Porosity

To illustrate the fact that, with increasing fibre content, the porosity of the specimen will be increased; in this part the porosity for several specimens are given. The full details of calculation for specimen K8 is illustrated in following section. The method of calculation used for porosity has been taken from chapter 2.4 Claisse (2010).

Also, the results of calculated porosity were compared with porosity measured by Accupyc 1300 Helium Pycnometer in the laboratory.

5.3.3.1.1 Theoretical calculation of porosity for K8

Specimen K8 was made with a w/c ratio (after vacuum dewatering) of 0.35 and a cement content of 140 gr and fibre content of 11.2 gr. After curing time it was dried in 70 º C oven. The weight loss on drying was 16%. To calculate the porosity of the specimen:

Assumptions:

- Specific gravity of unhydrated cement is 3.15
- Specific gravity of hydrated cement is 2.15
- Water combined with the cement in a ratio of 1:4
- Specific gravity of kraft fibres (table 3-1) is 1.5

All calculations are made in table 5-1:

Table 5-1 Calculated values to find porosity of specimen K8

Materials	Before hydration		After hydration and drying	
	Mass (kg)	Volume(lit)	Mass	Volume
Cement	0.14	0.044	0.072	0.023
Water	0.049	0.049	0.000	0.000
Hydrated Cement	0	0.000	0.085	0.039
Pores	0	0.000	0.000	0.031
Limestone Powder	0	0.000	0.000	0.000
kraft fibres	0.0112	0.007	0.011	0.007
Acrylic fibres	0	0.000	0.000	0.000
Total	0.20	0.10	0.17	0.10

Thus the volume of the cement and other materials can be calculated by mass/density.

As the water/cement ratio is 0.35, the mass of water would be M_w= 0.35 * .140.

Total mass and volume before hydration can be calculated as M_T = .20 (kg) and V_T = .10 (lit).

Loss of water after the specimen was dried, according to the weight loss of the specimen on drying, is 0.16%. This means the amount of lost water is 0.16* 0.2= .032 (lit).

The mass of combined water = total water- loss water = 0.049- 0.032= 0.017 (lit).

The assumed water combines with the cement in a ratio of 1:4.

Thus, the mass of cement which has hydrated = 4*0.017= 0.068 (kg).

Not all of the cement will hydrate. The extent of the hydration may be measured by weighing the hydrated sample after drying it. This means unhydrated cement = 0.14 - 0.068= 0.07 (kg).

The total mass of hydrated cement with considering combined water = 5 × 0.017 = 0.085 (kg).

The bulk volume of the specimens before and after drying would be the same.

And the mass and volume of kraft fibres before and after hydration would be the same.

The volume of pores = total volume – volume of (cement+ hydrated cement + kraft fibres).

The volume of pores = 0.10- 0.023- 0.039- 0.007= 0.03 (lit).

The porosity = (volume of pores)/ (total volume) * 100 = .03/ 0.10 * 100 = 30%.

5.3.3.1.2 Experimental porosity measured in the Laboratory

Porosity is defined by Volume $_{(air)}$ / Volume $_{(total)}$ ratio and can be calculated by

Porosity = (S.G – D.D)/ (S.G) Equation 5-2

Where

S.G : Specific gravity which is equal Mass / Volume $_{(net)}$

D.D : Dry density which is equal Mass / Volume $_{(total)}$

And Volume (air) = Volume $_{(total)}$ – Volume $_{(net)}$ Equation 5-3

Specific gravity of specimen K8 was measured by Helium Pycnometer and dry density was also calculated by measured weight and dimensions of the specimen.

S.G = 2.12

D.D = 1.6

And based on E.Q 5-3, porosity would be 24.5%.

This result shows, the theoretical calculated porosity (30%) for this specimen (K8) is a bit more than real porosity (24.5%) measured in the laboratory. This difference could be related to assumption of theoretical calculation which already mentioned.

As a result of time limitation, only some specimens were selected for this test. In table 5-2 the results of measured porosity for selected groups are given.

As can be seen in table 5-2, with increasing fibre content, porosity of the specimen increases and replacing limestone powder and/or silica fume for cement may also lead to a reduction in the porosity for the range of mixes studied.

Table 5-2 Porosity measured by helium pycnometer for selected specimens

Mix Code	Porosity (%)
K8	25
K8-L10	22
K8-L20	20
K8-M3	23
K8-M9	21
K8-L10-M3	21
K8-L10-M6	20
K8-L10-M9	20
K4-AC3	24
K4-AC3-L10	23
K4-AC3-L20	22
K4-AC3-M3	24
K4-AC3-M9	23
K4-AC3-L10-M3	22
K4-AC3-L10-M9	20

5.3.4 Moisture content

The moisture content for specimens was tested, as specified in the procedure outlined in section 4.4.2.4. The average of specimens in each group is shown in figures 5-63 and 5-64.

As seen in figures 5-63 and 5-64, maximum moisture contents are observed in specimens containing a high amount of silica fume and/or limestone powder. In figure 5-63, the range of moisture contents for all groups, excluding control specimens (neat cement), is between 3.8% and 5%, which is insignificant. Introducing acrylic fibres into the matrix (figure 5-64) causes a slight reduction in the range of moisture content to between 3% and 3.9%, which is close to the control specimens.

Investigation into the microstructure of fibres and the matrix shows that cellulose fibres can absorb and release moisture. Once the moisture penetrates inside the composite materials, the fibres tend to swell. The matrix structure can also be affected by the water uptake by processes such as chain reorientation and shrinkage. Due to the effect of the water molecules, the structure and properties of the fibres, matrix and their interface could be affected. Moisture penetration into fibre cement board may occur in three ways. The first way is due to the diffusion of water molecules inside the microgaps within cellulose fibres' lumen and polymer chains. The second common mechanisms are capillary transport into the gaps and flaws at the interfaces between fibres, particularly when the fibre content increases. The third way is water transportation by microcracks in the matrix, formed during the compounding process and cement hydration (Espert et al. 2004).

Based on the aforementioned mechanism of moisture penetratation, it seems the moisture content of the specimens could be correlated with capillary action so that in specimens containing a high value of super fine particles (i.e. silica fume and/or limestone powder), much more moisture enters the matrix as a result of capillary action. Therefore, after drying specimens in the oven, that uptaken moisture is evaporated. Whereas, in specimens without limestone powder or silica fume, the fissures and flaws in the fibre-matrix interface are too big to be affected by capillary action.

According to the capillary suction formula (Claisse 2010), the height of liquid H which can be lifted is given by

$$H = 2T / (\rho r g) \qquad \text{Equation 5-4}$$

where

T: surface tension

ρ: density of liquid

r: radius of void

g: acceleration of gravity

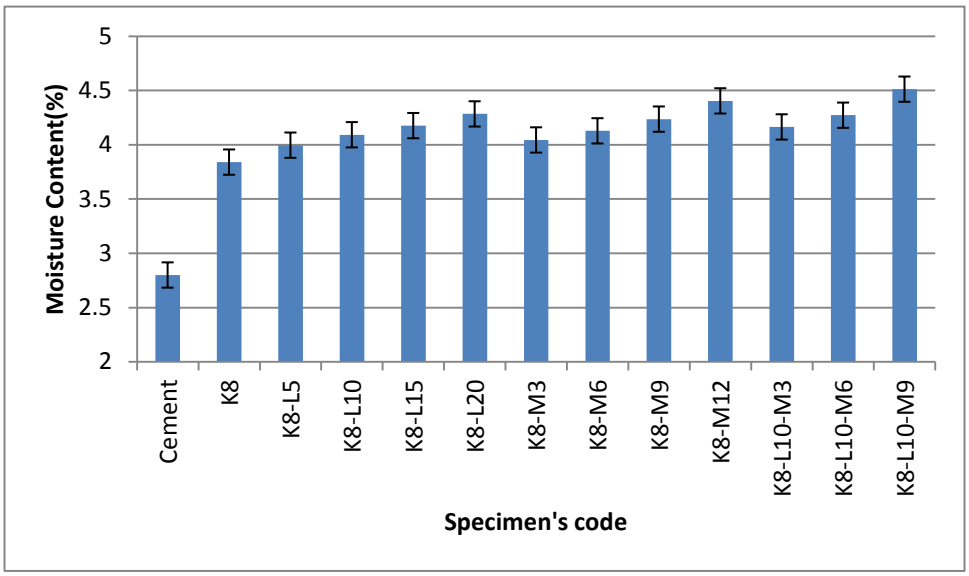

Figure 5-63 Moisture content of FCB reinforced by kraft fibres in conjunction with silica fume and limestone powder

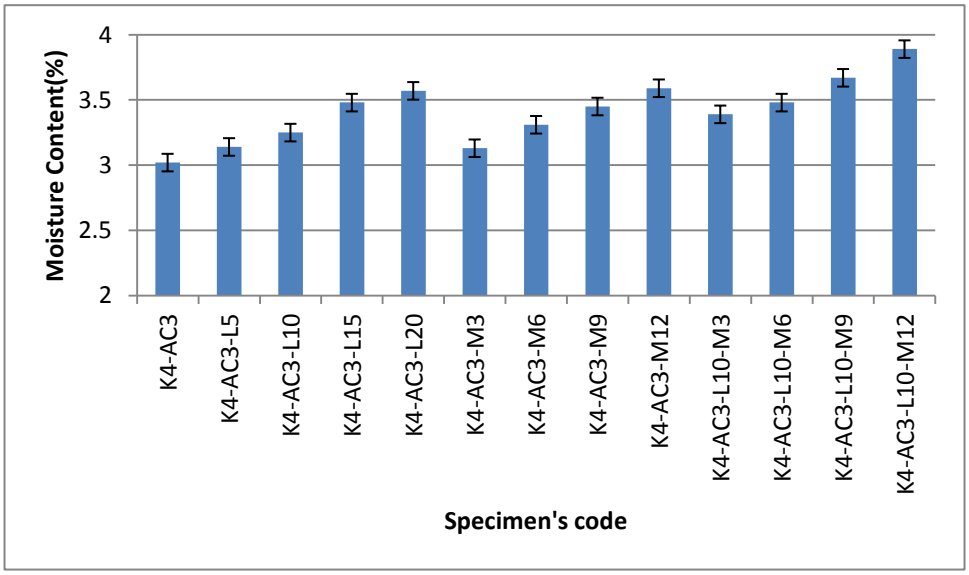

Figure 5-64 Moisture content of FCB reinforced by kraft and acrylic fibres in conjunction with silica fume and limestone powder

As can be seen, with a decrease in the radius of voids, the height at which capillary action lifts water increases. This confirms the statement already made regarding water absorption. Comparing figures 5-61 and 5-60 with 5-63 and 5-64 shows that specimens containing a high value of super fine particles present low water absorption. In other words, very small voids in specimens do not allow water to penetrate the specimen when it is submerged; however ambient air moisture can be sucked into the specimen as a result of capillary action when it is exposed to humid air.

According to Iranian national specification No. 575 moisture content of cement board should be less than 5%.

Referring back to figures 5-57 and 5-58, it can be observed that the introduction of silica fume and/or limestone powder leads to an increase in density, resulting in big voids being filled by particles and only small voids (capillaries) being left in the matrix and thus the moisture content increases.

Larger areas of porosity and voids allow water to enter the matrix as a result of water pressure when the specimen is submerged. Therefore, water absorption and its resulting effects can contribute to the loss of compatibility between the fibres and the matrix, which results in the de-bonding and weakening of the interface adhesion. These imperfections can be important during the service life of the products.

The results of water absoption test infigure 5-61 and 5-62 showed that the specimens, particularly those containing silica fume and/or limestone powder, present an appropriate

behaviour against water absorption, since no important difference was observed between the control specimen and the fibre-cement specimens.

5.4 Mechanical durability test

Long-term durability is one of the most important characteristics of cement board, as many of these products are exposed to different weather conditions. The best method to analyse the long-term performance of these composite materials is accelerated life cycle testing (Mohr et al. 2005), which represents natural different weather conditions, such as wet-dry cycles, freezing and thawing in cold weather.

Cyclic freezing and thawing in cold regions is considered as one of the most damaging environmental conditions for cement board.

The main aim of this section is to assess the mechanical durability of those specimens that presented the best performance in the aforementioned physical and mechanical properties in previous sections. According to BS EN 494 (2007), at least twenty specimens are required for each freeze-thaw testing, therefore only three different mixes were selected for this test.

5.4.1 Freeze-thaw

The results of freeze-thaw testing on three selected mixes, which experienced rapid, repeated (as many as 100) freezing and thawing cycles, are shown in Table 5-3 and the corresponding graph is in Figure 5-65.

Table 5-3 Flexural strength of specimens for freeze-thaw testing

Specimen's code	Mean flexural strength (normal condition)	Mean flexural strength (after freeze-thaw cycles)	L1: (normal)	L2: (freeze-thaw)	R_L=L2/L1
K8-L10-M3	8.88	6.9	9.01	6.52	0.72
K4-AC3-M9	10.22	6.79	10.43	6.61	0.63
K4-AC3-L10-M3	10.34	7.42	10.34	7.10	0.69

As can be seen in table 5-3, in addition to having the highest flexural test, the chosen mixes were determined from three different categories. The first one (i.e. K8-L10-M3) contains only kraft fibres and additives, the second one (i.e. K4-AC3-M9) contains kraft fibres, acrylic fibres and only silica fume and the third one includes both types of additives, kraft fibres and acrylic fibres.

As already mentioned in section 4.4.3, two important parameters based on the analysis of variance for 95% confidence level are L1 and L2, calculated from the results of the flexural strength for ten specimens in each group (according to eq. 4-6 and eq. 4-7).

- L1 is the upper estimation of the mean breaking load or bending moment at 95% confidence level of the reference lot (first lot in normal condition).
- L2 is the lower estimation of the mean breaking load or bending moment after freeze-thaw cycles at 95% confidence level (second lot).

According to this standard the ratio, R_L (R_L = L2/L1) shall be not less than 0.70.

The results in table 5-3 show that the group K8-L10-M3can satisfy standard requirements (R_L =0.72>0.7) and the group K4-AC3-L10-M3 is within the threshold of the standard value (R_L =0.69 ≈ 0.7). It seems this group may meet standard requirements and could be accepted. If the test is repeated with more precision, it is expected to obtain an R value of more than 0.69; however, much more research needs to be done to find the flexural performance of FCB under freeze-thaw cycling.

The only group which couldn't satisfy the standard requirement is K4-AC3-M9. For this group, R_L =.63, which is substantially less than 0.7.

Therefore two mixes out of three investigated mixes performed desirably under repeated freeze-thaw cycles.

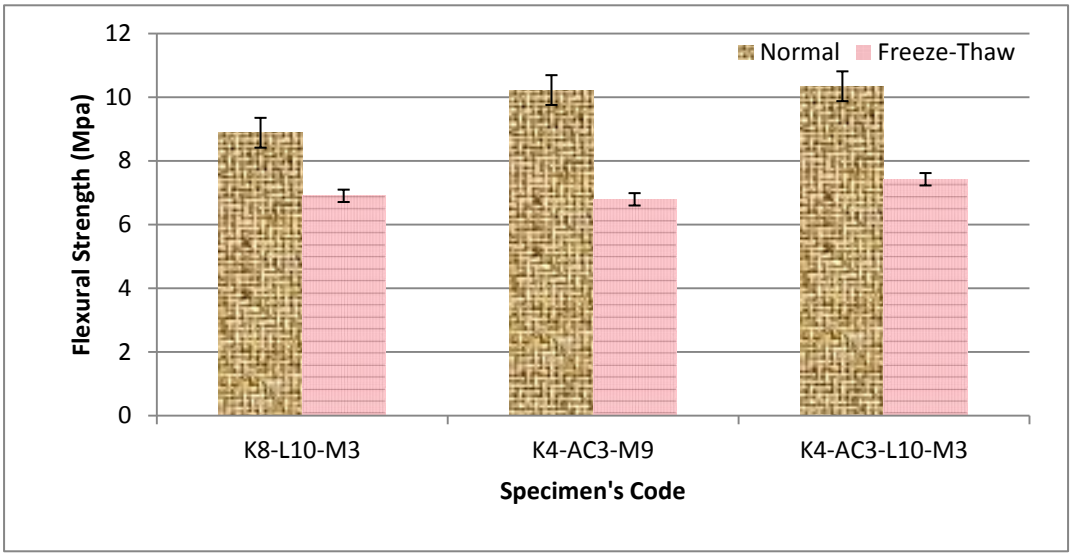

Figure 5-65 The mean flexural strength of chosen mixes in freezing and thawing test

It seems the results of this test are relatively consistent with the previously carried out physical tests. For instance, the density of K4-AC3-M9 is a bit less than both K8-L10-M3 and K4-AC3-L10-M3. In addition, the results of moisture movement and water absorption are compatible with this result. As already mentioned the weakness of K4-AC3-M9 in freeze-thaw testing rather than two other groups was proved by slightly greater moisture movement and water absorption.

This behaviour may be due to the presence of voids in the matrix as shown in figure 5-66. In this first group (K8-L10-M3), the tiny channels and voids, particularly the disjointed areas resulting from the weak bond in the fibre-matrix interface during freeze-thaw cycling, were connected to each other so that the voids joined to the surface of the composite. This made it easy for water to penetrate the matrix. In those two groups that approximately passed the standard, there were some voids too but they were not connected to each other so their performance was somewhat better.

It seems that one reason for this behaviour is associated with different particle sizes and their performance in the matrix; so, in specimens containing both acrylic and kraft fibres, the combination of limestone powder and silica fume could make the matrix a bit denser rather than when solely silica fume is used.

In specimen K8-L10-M3, which does not have any acrylic fibres, as a result of cellulosic structures and fibrillation properties, there is appropriate bonding within the matrix and the kraft fibres but it seems that, when acrylic fibres are introduced into the matrix, silica fume in conjunction with limestone powder can create better function.

A: Voids restrain access to the surface (less permeability and high porosity)

B: Voids allow access to the surface (high permeability and porosity)

Figure 5-66 Schematic distribution of voids in different mixes

In the procedure of freeze-thaw testing, cement board may allow substantial amounts of water to ingress. The tubular structure of cellulose fibres and its nature allows water to be absorbed (Smook 2002). The bond within the fibres and the matrix weaken as a result of expansion and contraction of the fibres and existing water in the matrix, consequently the flexural strength of the specimens reduces.

The conclusions derived from this test regarding the effects of kraft and acrylic fibres, silica fume and limestone powder on resistance to freezing and thawing show that the laminated structure of cement board, which has a small thickness and a large surface exposed to weather conditions, makes it vulnerable to freeze-thaw attack. In general, one of the ways to increase its

resistance against freeze-thaw cycling is to restrain the access of the pores and voids to the surface.

It should be noted that durability against freezing and thawing for cement board has been evaluated by a limited number of researchers (Soroushian et al. 1994; Kuder et al. 2003; Shah et al. 2004). All conducted research shows that cement board is relatively susceptible to the freezing and thawing environment and reducing permeability could be the best way to improve its resistance against freeze-thaw cycles. To overcome this weakness they also suggested pressing the specimens after forming them in the mould or during the Hatschek process. This may expel excess water and improve fibre-matrix bonding, thus reducing the permeability.

Of course that suggestion was already applied in this research. As mentioned in section 4.2.2, during sample preparation and casting in the laboratory, in order to mitigate this potentially detrimental effect, a 10 Kg weight was applied when the slurry was in the mould, to add pressure to the specimen and increase the amount of water withdrawn by the vacuum machine.

Chapter 6; Factory testing of laboratory results

In this chapter, the procedure of manufacturing pilot cement boards in a cement board factory based on the outcome of this research is described.

It is obvious that making specimens in the laboratory with 200gr cement, 10 gr fibres and 30 gr additives is totally different with making full-scale cement board where the minimum ingredients are 450 Kg cement and 60 Kg fibres. In addition, the procedure of manufacturing full-scale cement board in the factory is the Hatschek process, while in the laboratory a different method based on a slurry vacuum dewatering process was applied.

Full-scale trial specimens were manufactured in the Sarit factory, which is one of the asbestos cement board factories in Iran. This factory produces around 1.5 million square metres of corrugated cement board and 60,000 asbestos cement tiles (dimensions are 600*300*4 mm) annually.

This factory was established in the north of Iran in 1993 and most of the equipment in this factory was imported from Austria.

As it is very expensive to make full-scale cement board in a factory, only the best two mixes obtained from the outcomes of the laboratory research were chosen for the full-scale trial. These two mixes were:

- K8-L10-M3
- K4-AC3-L10-M3

The procedure of manufacturing full-scale cement board in the factory was divided into following stages:

1. preparation of fibres
2. preparation of Hatschek machine
3. production of full-scale cement board
4. primary inspection of the produced cement board
5. flexural strength test on cement board

In the next sections, more details of each of above mentioned stages are illustrated.

6.1 Preparation of fibres

In order to extract the kraft pulp fibres from cardboard, 40 Kg of waste cardboard was provided for each mix and then shredded manually into small pieces of approximately 100*100 mm. This shredded cardboard was submerged in water for 48 hours.

Figure 6-1 Preparation of kraft pulp fibres from shredded cardboard

As there was no appropriate pulping machine in the factory, making pulp was carried out by the easiest traditional way, as shown in figure 6-2. This took about three hours.

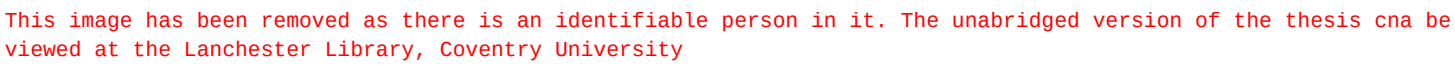

Figure 6-2 Pulp being prepared from waste cardboard in the traditional way

In order to investigate the quality of prepared pulp for use in the Hatschek machine, it was sampled every fifteen minutes. This sampling was continued until the cellulose fibres were observable in the pulp by the naked eye, as shown in figure 6-3.

Figure 6-3 Visual inspection of pulp quality to make it usable in Hatschek machine

Then, after preparation of the kraft pulp, the acrylic fibres and the kraft pulp were introduced into the turbo mixer.

The question that may arise when waste cardboard is used in this research is ‘whether all types of waste cardboard are usable, because waste cardboard can be used to produce new cardboard several times. As waste cardboard is used many times, the length of the cellulose fibres becomes shorter and shorter and some of the mechanical properties of fibres may become weaker and weaker, so this would affect the mechanical properties of cement board made out of these weak fibres.

To answer this question, a study was carried out by the author on how to reprocess waste cardboard to make new cardboard. This study showed that, as waste cardboard is reused many times, its length and strength properties reduce gradually (Smook 2002) . In paper-making

factories this weak type of waste cardboard cannot be used solely in production of new cardboard so it is necessary to add virgin fibres with high qualities (i.e. long length and high tensile strength) to these weak fibres. The weaker waste cardboard, the more amounts of virgin fibres needs for blending. Therefore, all types of cardboards should have minimum strength properties to be manufactured in the paper-making factories.

6.2 Preparation of Hatschek machine

As the Hatschek machine belongs to a factory that continuously produces asbestos fibre cement, there were large amounts of asbestos fibres on the machine, mixer, felt, vat, sieve cylinder and other parts. It was necessary to remove as many asbestos fibres as possible (figure 6-4) because the production of non-asbestos cement board is the main objective of this research and the presence of asbestos even in small quantities may lead to disruption to the procedure.

Figure 6-4 Washing the Hatschek machine to remove all remaining asbestos fibres before producing non-asbestos cement board

6.3 Production of full-scale cement boards

In this stage, the kraft fibres and/or acrylic fibres were put in turbo mixer. After 10 minutes, other materials such as cement, silica fume and limestone powder were added to the mix and then for 5 minutes all materials were blended with each other. During this procedure, sampling of the mix was done to make sure the quality of the slurry reached the desirable level. This procedure was carried out in association with skilled technicians who have worked with asbestos cement board for many years. Then the slurry was removed from turbo mixer and conveyed to the Hatschek machine. In this stage, with trial and error, the required adjustments to the speed of rolls, power of vacuum pump and the speed of the running felt were done to form a tiny layer on the running felt. Then, as the sieve cylinder rotated, a slurry layer was deposited on its surface

and its continuous application on the running felt turned it into a coherent layer as water was sucked by the vacuum machine into the ‘dry’ side of felt. The layers were built up into a laminate by winding on the cylinder (mandrel), until the required thickness was achieved, which was about 5-7 mm. Then cutting and shaping according to normal production of the factory (110 * 250 cm) were conducted. These procedures are shown in figures 6-5 and 6-6.

Figure 6-5 Forming the tiny layers on the running felt on the Hatschek machine

Figure 6-6 Layers built up by winding on the cylinder (mandrel), until the required thickness was obtained

One of the most important phases in production is the possibility of continuous production of the cement board with the Hatschek machine. Because, in some cases, after making two or three specimens, some problems may occur, such as disruption to the Hatschek machine operation and/or transforming the smooth surface of the specimens into a patchy and non-dense surface.

Based on the experience of technicians, at least 10 sheets must be manufactured to make sure of the possibility and feasibility of continuous production.

After making three cement boards, a problem occurred in the production line. A large amount of bubbles were formed in the vat and it made some problems in the sieve cylinders so that ample slurry could not reach the running felt (figure 6-7).

Figure 6-7 Bubble forming in the vat due to cellulose fibres after making several trial cement boards

To overcome this problem, an amount of silicon based antifoam, 0.5% on cement weight, was applied. No significant problem was observed after this. As seen in figure 6-8, after using antifoam, continuous production of the cement board was established.

After overcoming all the aforementioned problems, more than 10 cement boards (dimensions: 2.5 * 1.1 m) were manufactured successfully for each proposed mix proportion.

Figure 6-8 Continues production of non-asbestos cement board was established

Figure 6-9 Corrugation of sheets by adjusting the moisture content

These produced cement boards had the same appearance and thickness and were also compatible with the existing Hatschek machine in an asbestos cement board factory (figure 6-10).

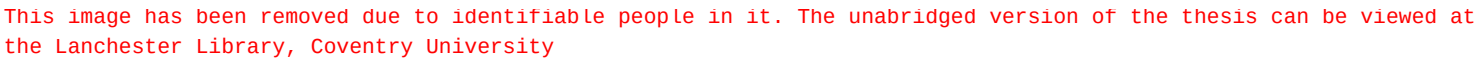

Figure 6-10 Success in manufacturing non-asbestos cement board in the factory based on the outcome of this research

The results of the flexural strength test for 28 days and 6 months after manufacturing are summarized in table 6-1.

As seen in table 6-1, both groups satisfy the required MOR according to BS EN 12467. As can be observed, the result of K4-AC3-L10-M3 is a bit greater than K8-L10-M3. This may be due to the effect of acrylic fibres which are stronger and longer than kraft pulp fibres.

As already mentioned, most asbestos cement board factories in Iran only carry out the MOR test as quality control of products.

Table 6-1 Flexural strength of corrugated sheets at 28 and 180 days

Group	Sheet number	Flexural Strength 28-day (MPa)	Flexural Strength 180-day (MPa)
K8-L10-M3	1	16.2	17
	2	15.8	16.2
	3	16.4	17.5
	4	15.4	16.4
	5	16.3	16.7
	Average	**16.02**	**16.76**
K4-AC3-L10-M3	1	17.8	18.2
	2	17.3	18
	3	16.7	18.3
	4	17.6	18.1
	5	17.4	18.7
	Average	**17.36**	**18.26**

It should be noted that it is impossible to do any tests for the corrugated cement board in the laboratory as it needs big size cement boards and particular equipment that is not found in the laboratory.

Figure 6-11 shows the particular equipment for the flexural test of corrugated cement sheet in the factory.

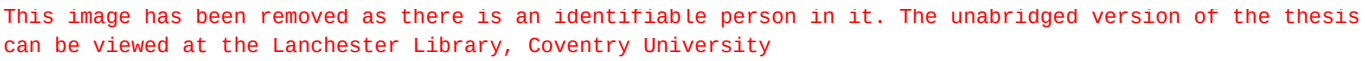

Figure 6-11 Flexural strength testing for non-asbestos cement board in the factory

A brief economic comparison carried out in the local market between asbestos cement board and the new materials (based on the outcome of this research) shows that, at present, the price of asbestos after tax is 400 to 700 GBP per ton. The amount of asbestos fibres used to produce cement board, depending on the factory and mix proportions, is 12-15 % by the weight of cement. The kraft pulp fibres derived from waste cardboard is very cheap (less than 200 GBP). The price of acrylic fibres is 1500-1800 GBP per ton but, as already mentioned, acrylic fibres are used for just 3% of the cement weight. The price of silica fume is approximately identical to cement and the price of limestone powder is often less than cement. So, replacing these proposed materials and fibres for asbestos in cement board can be cheaper or equal to the price of asbestos in cement board production. It should be borne in mind that asbestos fibres are harmful for human health while these proposed materials (particularly the kraft pulp fibres derived from waste cardboard) are generally safe for humans.

Chapter 7; Summary and contributions to knowledge

In this research an effort was made to replace asbestos with other accessible, cheaper and environmentally friendly fibres. And also these fibres needed to be compatible with the Hatschek process, which is the most widely used process in cement board production.

This research concentrated on using natural and synthetic fibres as alternatives to asbestos fibres in cement board. In the first phase of this project, kraft pulp fibres obtained from waste kraft cardboard were selected as the best fibre within the four selected fibres (i.e. wheat, eucalyptus, bagasse and waste cardboard) to reinforce cement board.

In the second phase, interaction of the two types of synthetic fibres (i.e. acrylic and polypropylene fibres which are available in the Iranian market) in conjunction with kraft fibres were investigated. It was concluded that acrylic fibres has an appropriate compatibility with kraft fibres to enhance FCB's mechanical properties.

In the third phase of this research an attempt was made to enhance physical and mechanical characteristics of FCB using limestone powder and silica fume.

In the last phase of this research, the best laboratory mixes were used in an asbestos cement board factory and several full scale non- asbestos cement boards were successfully manufactured.

Three important outcomes of this research that could be considered as contributions to knowledge are as follows:

1- To the best knowledge of the author, the laboratory equipments adopted for the experimental work in this research were developed as the first of its kind in the world; hence the procedure of making the specimens is based on dewatering system which is roughly similar to Hatschek process
2- The kraft pulp fibres derived from waste cardboard was applied for the first time to produce cement board
3- It is the first time that acrylic fibres in conjunction with waste cardboard, silica fume and limestone powder were applied to produce fibre cement board.

Chapter 8; conclusion

The conclusion of the aforementioned phases is summarized as follows:

1. Maximum flexural strength (or MOR: modulus of rupture) for control specimens made solely by cement (neat cement without any fibres) is about 3 MPa and its failure is brittle.
2. The use of some waste agricultural fibres (i.e. bagasse fibre) in cement board can increase MOR and improve flexural performance.
3. The maximum percentage of waste agricultural fibres that can be used in the cement matrix is 4% by the weight of cement. A higher percentage creates problems in manufacturing specimens so that, as a result of the low density of these fibres in comparison with the slurry, they float on the slurry and non-uniform distribution of fibres in the matrix is observed.
4. The flexural performance of the cement board reinforced by bagasse fibres is better than cement board made out of wheat or eucalyptus fibres. This is due to high tensile strength and the high aspect ratio of the bagasse fibres in comparison to the wheat and eucalyptus fibres.
5. In addition to the three types of agricultural waste fibre (i.e. wheat, eucalyptus and bagasse fibres), waste cardboard (i.e. kraft pulp fibres) was also used. The flexural

strength and area under the curve of cement board reinforced by kraft pulp fibres are much higher than those of agricultural waste fibres. This is due to some characteristics of kraft pulp fibres such as their high aspect ratio and low amount of lignin.

6. kraft pulp fibres can be used up to 14% of the weight of cement due to the high consistency of the kraft fibres with the cement matrix. By increasing the amount of kraft fibres in the specimens, ductility, water absorption, moisture content, moisture movement increase and density decreases.
7. The optimum percentage of kraft fibres reinforcing cement board to gain the highest flexural strength is about 8% by the weight of cement. This will result in a MOR greater than 8 MPa and appropriate performance.
8. In some cases, using both silica fume and/or limestone powder may create better performance in the matrix. But this optimum value is dependent on many factors such as the type of fibre, fibre content, particle size of silica fume, etc.
9. Applying synthetic fibres in conjunction with kraft fibres in the cement matrix leads to an increase in area under the curve and in some cases an increase in flexural strength.
10. In general there are two important differences between cellulose fibres (i.e. kraft pulp) and synthetic fibres (i.e. acrylic fibres). The first one is related to the fibrillation properties. In contrast to acrylic fibres, cellulose fibres have high potential to be fibrillated. The second is that cellulose fibres are hydrophilic due to the presence of -OH groups at their surfaces, whereas synthetic fibres are hydrophobic. As a result of these

differences, cellulose fibres have a high consistency with cement media and can be used as reinforcement in the cement matrix solely or in conjunction with synthetic fibres.

11. In the manufacturing procedure in the laboratory, the distribution of fibres throughout the specimens occurred in three dimensions while in the Hatschek process, as cement board is formed by several tiny layers, dispersion of the fibres occurred on the surface of specimens in two dimensions. This means the Hatschek process has greater efficiency by using fibres in 2D in comparison with designated laboratory equipment. The presence of fibres parallel to the thickness of the sheet is not beneficial for mechanical properties. Therefore, finding the optimum fibre content in cement board production using the Hatschek process can be determined by trial and error in the factory.
12. Calculating the amount of residual water in the matrix after it was subjected by the vacuum pump in the laboratory was important in analysing the results because, during the procedure in the laboratory, the small vacuum pump may lose some suction and not work with maximum efficiency during several hours. So, the time of suction to remove the residual water from the specimens may need to be increased later. It should be noted that, by subtracting the sucked water from the initial water, the amount of residual water can be calculated.
13. The highest MOR result was obtained when the specimens were reinforced solely by 8% kraft fibres; in some cases, as a result of interaction between acrylic and kraft fibres, the blending of kraft and acrylic fibres enhances flexural performance rather than specimens reinforced solely by kraft fibres. This can be found by trial and error for different types of

fibre. In this research, 4% of kraft fibres (by the cement weight) in conjunction with 3% of acrylic fibres present the highest MOR.

14. Specimens containing kraft and polypropylene fibres show high values in ductility; however, their flexural strength is less than 7 MPa. It seems this occurs due to a low Young's modulus and great elongation at the break of these fibres.
15. As the density of polypropylene is less than water (0.9 gr/cm^3), these fibres float on the slurry and cannot distribute properly, particularly when a high value of these fibres is used.
16. Using long length polypropylene fibres (i.e. 6 mm) in the cement matrix causes a balling phenomenon so that these fibres tie together and cannot distribute uniformly throughout the matrix.
17. When a large amount of kraft fibres are put in a high-speed mixer, large amounts of bubbles is generated. To overcome this problem, using small amount of silicon-based antifoam (about 0.5% by the cement weight) can be helpful.
18. The density of all specimens is in the range 1.56-1.74 gr/cm^3 and the small variation between the specimens is due to the amount of limestone powder and/or silica fume. Also, the density of specimens containing both kraft and acrylic fibres is in the range 1.56-1.62 gr/cm^3 which means they are very close to each other.
19. The moisture movement of specimens, which is related to the expansion of their length due to the changes in moisture content, is equal to or less than 0.1%.

20. The water absorption of specimens increases with increasing fibre content. The water absorption of the control specimen (neat cement without any fibre) is about 13% and the maximum water absorption of 17% belongs to the specimens containing solely 8% kraft fibres. The introduction of limestone powder and/or silica fume causes a reduction in water absorption to about 13% which is identical to the control specimen.
21. The moisture content of specimens, excluding the control specimen, is between 3.8% and 5%. For the control specimen, the moisture content is 2.8%. The inclusion of acrylic fibres in the matrix causes a slight increase in the range of moisture content to about 3% to 3.9%, which is closer to the control specimen.
22. The results of freeze-thaw testing show that two out of the three chosen groups could satisfy standard requirements. The first group is specimens containing 8% Kraft, 10% limestone powder and 3% silica fume. The second group is specimens containing 4% Kraft, 3% acrylic, 10% limestone powder and 3% silica fume. All percentages are calculated by the cement weight. The only group that couldn't satisfy the standard requirement was specimens containing 4% Kraft, 3% acrylic fibres and 9% silica fume.
23. Manufacturing full-scale specimens in the asbestos cement factory based on the outcome of this research shows that the waste cardboard and acrylic fibres have the potential to be used as an alternative to asbestos in cement board. The results of the conducted tests illustrate that the cement board reinforced by kraft and/or acrylic fibres could satisfy standard requirements.

24. Based on this research, the asbestos cement board factory could modify their production to non-asbestos cement board with only a few changes to their production line such as providing a pulper, refiner and other small changes to some equipment.
25. By using recommended proportion of fibres, cement, silica fume and limestone powder, flexural strength of control specimen (neat cement without any fibres) could increase as much as 4 times in the laboratory and would be about 6 times in a fibre cement factory using Hatschek process.

In general, this research has identified characteristics of different types of fibres when they are used in conjunction with cement, limestone powder and silica fume.

It should be noted that, based on visits to several asbestos cement factories and negotiations with their managers in Iran, the proportions of materials used to produce asbestos cement board are different to each other; however, the final products of all of them have the same characteristics. For example, in some of the factories, 12, 13 or 14% asbestos fibres is used. Interestingly, even when each factory imports new asbestos fibres (usually every three months), the factory has to do several trial and error tests to find the best proportions because the properties of different asbestos fibres are not identical.

Therefore, at the end of this report, it should be noted that the proposed mixes for replacing asbestos in cement board need to be modified by each asbestos cement factory as there are many parameters influencing the products' properties such as type of cement, fibres, additives and existing equipment in the factory. Therefore this research can be used as general guidance for all asbestos cement factories.

Chapter 9; Future research

- This research was only concentrated on three types of agricultural waste fibre and waste cardboard while there are many types of agricultural waste fibre such as flax, corn, sunflower, jute, banana, etc. In addition, in this research only two types of synthetic fibre were used so the feasibility of using other synthetic fibres could be studied. The effects of additives such as silica fume and limestone powder were investigated in this research but the particle size of these materials may change and, with that change, the optimum proportion for mixes may vary. Reducing the permeability of cement board with the use of additives and/or by applying pressure on specimens could be investigated in future. Synthetic fibres normally don't have good bonding with hydrated cement but they may be treated by some admixtures and additives. It is recommended that other types of agricultural waste fibres in conjunction with other types of synthetic fibres and different types and amount of additives are studied in future research.
- In this research cellulose fibres were used without any flocculants or sizing agents as no available literature in this area could be found for the Iranian by-products. Also using these admixtures would increase the cost of production process. However it seems using sizing agents such as poly-acryl-amides, styrene-acrylate copolymers and alkyl ketene dimer as reported by other researchers (Negro et al. 2005) could enhance the fibre-cement interfacial bonding because waste cardboard is made of cellulose fibres.

- In this research, micro silica fume which has two effects (filler and pozzolanic performance) was used. It seems using nano silica fume which is stronger in both aforementioned effects may lead to better characteristics.
- In this research, an attempt was made to find optimum amount of fibres and additives to provide the highest flexural performance of FCB, the approximate optimum recommended value needs to be verified through more precise statistical methods. The roughly estimation for the required number of mixes (considering 4, 5, 4 and 6 amounts for acrylic fibres, kraft fibres, limestone powder and silica fume respectively) would be 840 mixes. Therefore to reduce the number of mixes suitable methods such as neural network should be applied.

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Appendix A; Flexural strength tables

The flexural strength of each group at 7 and 28 days obtained from the average of five replicated specimens are given in this section. The corresponding graphs for each group have already been given in chapter five.

A-1: Flexural strength (7 & 28 days) of laboratory specimens reinforced by waste natural fibres (fibre content is up to 4%).

groups	Average flexural strength	groups	Average flexural strength
C-7D	2.33	E4-7D	3.90
C-28D	3.12	E4-28D	3.79
W2-7D	2.89	B2-7D	4.81
W2-28D	2.60	B2-28D	4.40
W4-7D	4.05	B4-7D	5.25
W4-28D	3.52	B4-28D	4.73
E2-7D	4.26	E2-28D	3.71

A-2: Flexural strength (7 & 28 days) of laboratory specimens reinforced by waste kraft pulp fibres (fibre content is up to 14%).

groups	Average flexural strength	groups	Average flexural strength	groups	Average flexural strength	groups	Average flexural strength
C-7D	2.33	K4-7D	4.02	K8-7D	5.86	K12-7D	4.56
C-28D	3.12	K4-28D	5.28	K8-28D	8.14	K12-28D	6.20
K1-7D	2.58	K5-7D	4.35	K9-7D	5.45	K13-7D	3.80
K1-28D	3.50	K5-28D	5.83	K9-28D	7.51	K13-28D	4.80
K2-7D	2.89	K6-7D	4.74	K10-7D	5.12	K14-7D	3.60
K2-28D	3.84	K6-28D	6.32	K10-28D	7.10	K14-28d	4.52
K3-7D	3.26	K7-7D	5.20	K11-7D	4.82		
K3-28D	4.45	K7-28D	7.52	K11-28D	6.85		

A-3: Flexural strength (7 & 28 days) of laboratory specimens reinforced by waste kraft pulp fibres and polypropylene fibres (3mm and 6mm).

groups	Average flexural strength	groups	Average flexural strength
C-7D	2.33	K8PP1.5-3mm-7D	4.75
C-28D	3.12	K8PP1.5-3mm-28D	6.08
K8-7D	5.12	K8PP0.5-6mm-7D	4.27
K8-28D	8.14	K8PP0.5-6mm-28D	5.00
K8PP0.5-3mm-7D	3.42	K8PP1-6mm-7D	3.88
K8PP0.5-3mm-28D	4.14	K8PP1-6mm-28D	4.93
K8PP1-3mm-7D	4.84	P8PP1.5-6mm-7D	3.98
K8PP1-3mm-28D	5.66	P8PP1.5L-6mm-28D	4.66

A-4: Flexural strength (7 & 28 days) of laboratory specimens reinforced by waste kraft pulp fibres and acrylic fibres.

groups	Average flexural strength	groups	Average flexural strength
K2-7D	2.89	K6-D7	4.74
K2-28D	3.84	K6-D28	6.32
K2AC0.5-7D	6.27	K6AC0.5-7D	5.00
K2AC0.5-28D	7.90	K6AC0.5-28D	6.20
K2AC1-7D	6.69	K6AC1-7D	5.22
K2AC1-28D	8.03	K6AC1-28D	6.37
K2AC2-7D	7.03	K6AC2-7D	5.61
K2AC2-28D	8.29	K6AC2-28D	6.50
K2AC3-7D	6.05	K6AC3-7D	5.79
K2AC3-28D	7.27	K6AC3-28D	6.83
K4-D7	4.02	K8-D7	5.86
K4-D28	5.28	K8-D28	8.14
K4AC0.5-7D	4.59	K8AC0.5-7D	3.39
K4AC0.5-28D	5.09	K8AC0.5-28D	3.73
K4AC1-7D	6.32	K8AC1-7D	5.35
K4AC1-28D	7.40	K8AC1-28D	6.15
K4AC2-7D	6.89	K8AC2-7D	5.53
K4AC2-28D	7.92	K8AC2-28D	6.52
K4AC3-7D	7.07	K8AC3-7D	5.75
K4AC3-28D	8.83	K8AC3-28D	7.07

A-5: Effect of additives on flexural strength (7 & 28 days) of laboratory specimens reinforced by waste kraft pulp fibres.

groups	Average flexural strength
K8-7D	5.9
K8-28D	8.1
K8-L5-7D	6.8
K8-L5-28D	8.5
K8-L10-7D	7.4
K8-L10-28D	8.8
K8-L15-7D	6.4
K8-L15-28D	7.8
K8-L20-7D	5.4
K8-L20-28D	6.9

A-6: Effect of additives on flexural strength (7 & 28 days) of laboratory specimens reinforced by waste kraft pulp fibres and acrylic fibres.

groups	Average flexural strength
K8-7D	5.9
K8-28D	8.1
K8-M3-7D	6.7
K8-M3-28D	8.0
K8-M6-7D	7.1
K8-M6-28D	8.5
K8-M9-7D	6.7
K8-M9-28D	7.6
K8-M12-7D	6.3
K8-M12-28D	7.1